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Advanced Controls for Residential Whole-House Ventilation Systems

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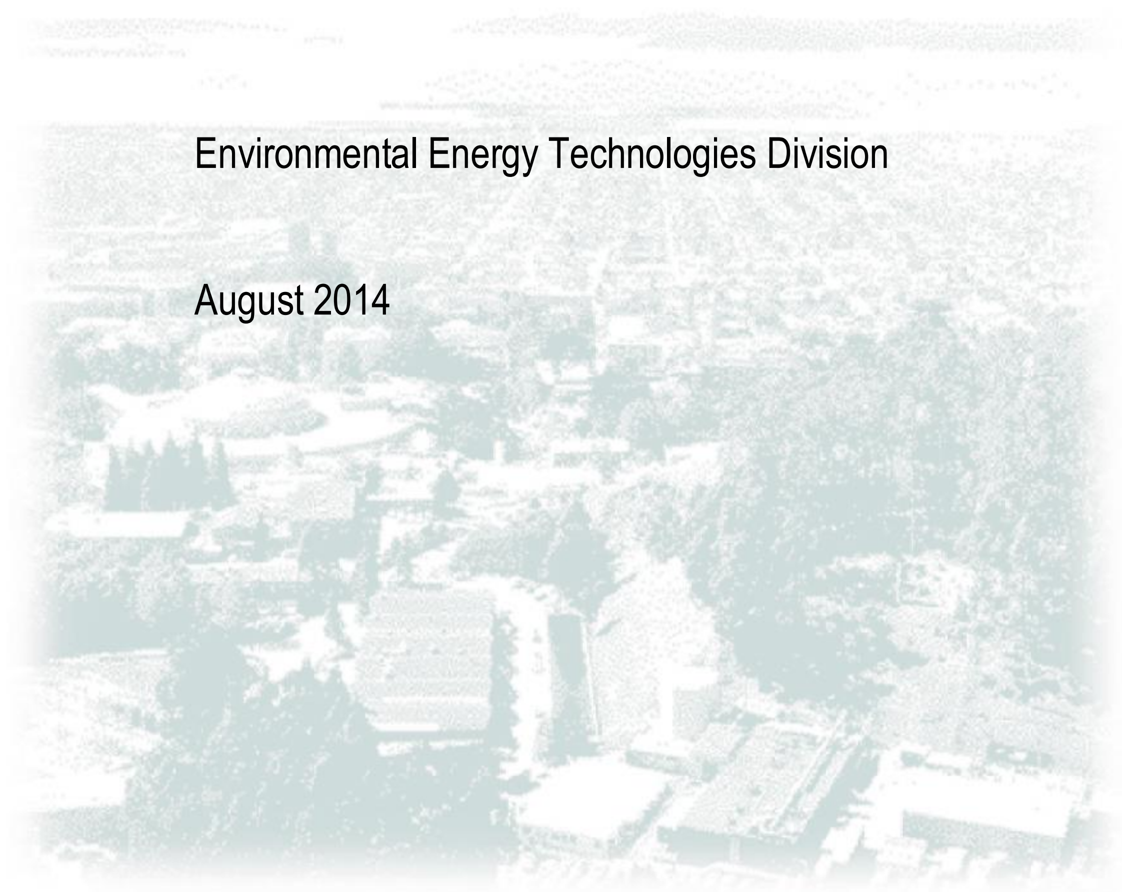

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ABSTRACT

Whole-house ventilation systems are becoming commonplace in new construction, remodeling/renovation, and weatherization projects, driven by combinations of specific requirements for indoor air quality (IAQ), health and compliance with standards, such as ASHRAE 62.2. Ventilation systems incur an energy penalty on the home via fan power used to drive the airflow, and the additional space-conditioning load associated with heating or cooling the ventilation air. Finding a balance between IAQ and energy use is important if homes are to be adequately ventilated while not increasing the energy burden. This study used computer simulations to examine RIVEC – the Residential Integrated Ventilation Controller - a prototype ventilation controller that aims to deliver whole-house ventilation rates that comply with ventilation standards, for the minimum use of energy. Four different whole-house ventilation systems were simulated, both with and without RIVEC, so that the energy and IAQ results could be compared. Simulations were conducted for 13 US climate zones, three house designs, and three envelope leakage values.

The results showed that the RIVEC controller could typically return ventilation energy savings greater than 40% without compromising long-term chronic or short-term acute exposures to relevant indoor contaminants. Critical and average peak power loads were also reduced as a consequence of using RIVEC.

KEYWORDS

Residential ventilation, ventilation controller, ASHRAE Standard 62.2, demand response

1. INTRODUCTION

Indoor air quality (IAQ) is a complex result of occupant activities, human responses, source emission, and contaminant removal. Two key methods to provide acceptable IAQ are ventilation and source control. Setting effective requirements for the implementation of these methods often requires an understanding of the materials and processes typically found in houses and the operational strategies of their occupants.

Newer homes have become more airtight in order to reduce heating and air-conditioning use. Consequently, they need ventilation systems to maintain IAQ. In response, building codes and standards such as ASHRAE Standard 62.2 (2010) increasingly require homes to have mechanical ventilation to provide acceptable IAQ. Generally whole-house exhaust or supply fans are used as they offer a cheap and simple engineering solution. However, these mechanical fans are usually operated for 24-hours per day and are not optimized for energy efficiency. Although there are some provisions for intermittent system operation, the standards basically assume that there will be a constant ventilation rate from a purpose-provided mechanical ventilation system for every hour of the day. The cost of providing mechanical ventilation, however, changes because of weather and the price (or value) of energy. The benefits of providing mechanical ventilation can vary during the day due to the operation of other devices that also provide some level of whole-house mechanical ventilation (for example, vented clothes dryers and kitchen range hoods), or the presence of outdoor air pollutants such as ozone or particulate matter. However, an integrated approach to looking at both residential IAQ and energy is usually lacking. A balance between operating costs and air quality issues can be optimized by using a controller for the whole-house ventilation system that can ventilate at different times of day in response to changing energy and IAQ impacts.

This study uses simulations to evaluate a prototype Residential Integrated VEntilation Controller (RIVEC) that optimizes operating costs and air quality. Building from previous work (Sherman and Walker, 2011), the control algorithms for RIVEC are optimized and additional control facilities, such as occupancy are developed.

2. BACKGROUND

RIVEC is a dynamic ventilation controller that attempts to address two opportunities to reduce energy consumption from residential ventilation:

1. Optimization of ventilation rates relative to ASHRAE Standard 62.2 - the only standard with guidelines for residential ventilation rates in the United States – by maximizing IAQ while minimizing energy consumption and maintaining compliance with ASHRAE 62.2

2. Demand response – the shifting (and stripping) of loads on the power distribution grids at times of peak power demand.

Residential Ventilation Standards

In its simplest form ASHRAE Standard 62.2 specifies a minimum continuous, mechanical, whole-house ventilation rate, $Q_{62.2}$, based on the size and occupancy of the house:

$$Q_{62.2} = 0.05 \cdot A_{floor} + 3.5\left(N_{br} + 1\right) \tag{1}$$

Where:

$Q_{62.2}$	=	fan airflow rate [L/s]
A_{floor}	=	occupied floor area of the home [m^2]
N_{br}	=	number of bedrooms

Although the standard specifies certain performance conditions for mechanical ventilation, it also allows the use of dual-purpose fans (one fan can simultaneously provide both local exhaust and continuous whole-house ventilation) to meet whole-house requirements. It also provides a methodology for using time-varying mechanical ventilation. However, ASHRAE Standard 62.2 does not account for the fact that, in a typical occupied house, a variety of activities independent of the whole-house ventilation system will also ventilate the home. This can include the use of kitchen and bathroom exhaust fans, economizers and clothes dryers. In addition, the standard does not take into account that temporarily reducing or eliminating mechanical ventilation at certain times of the day can be beneficial, for both energy-efficiency and air quality reasons. A potential solution is to use a ventilation controller that can monitor all of the mechanical ventilation flows in a home and adjust the whole-house ventilation rate accordingly. RIVEC takes full advantage of exogenous mechanical ventilation and shifts the operation of the whole-house ventilation system to desirable times of day by controlling the whole-house ventilation fan. The control method is based on original work by Sherman et al. (2009) during work carried out for the California Energy Commission's Energy Innovations and Small Grant Program.

Energy/Indoor Air Quality Tradeoff

The ventilation, heating and air-conditioning of buildings is one of the dominant uses of energy in the United States. Residential buildings account for 22% of total US energy consumption, with 54% of this attributed to space heating and cooling (DOE, 2011). The energy demand of existing technologies poses several key problems. Resultant CO_2 emissions are contributing to climate change and global warming. Diminishing fossil fuel reserves mean that the US has to seek alternative energy sources while maximizing the energy conversion of existing supplies. As the demand for fuel increases so does its economic cost. Recent residential construction methods have yielded tighter building envelopes that can save energy, but also create a potential for under-ventilation (Offerman, 2009, Sherman and Dickerhoff, 1994, Sherman and Matson, 2002). This under-ventilation directly and negatively impinges on IAQ by not removing contaminants from the indoor environment.

While energy conservation and efficiency are important, measures implemented must not be at the cost of IAQ. The World Health Organization (WHO) notes that the indoor environment represents an important microenvironment in which people spend a significant portion of their time each day. In general people spend 80% to 90% of their time in an indoor environment living, working or commuting (Bower, 1995, ASHRAE, 2005, Spengler et al., 1982, Szalai, 1972). As a result, indoor air pollution is more likely to contribute to population exposure to pollutants than the outdoor environment (World Health Organisation, 2005).

Ventilation of buildings introduces outdoor air into the occupied zone while displacing stale indoor air. However, the outdoor air typically needs to be conditioned to meet thermal comfort requirements so ventilation increases the heating and/or cooling load of the building. Clearly a balance needs to be met between energy consumption and IAQ.

Peak Energy Demand and Demand Response

Currently, there is a drive in the US towards reducing the maximum instantaneous load on power grids. 'Peak energy demand' refers to the time of day when loads on the gas and electricity distribution infrastructures reach a maximum. During the winter months this is typically between 4am and 8am when external temperatures are at their coldest and the heating demand is greatest. During the summer months the demand tends to reach a maximum between 2pm and 6pm when the cooling demand is greatest and consequently the air conditioning load is the highest.

During these peak periods the extra demand on the grid is met by increasing grid capacity via the operation of power plants with a higher marginal cost and higher CO_2 emissions. Use of these additional power plants increases the generation cost for each kilowatt-hour for the utility company. The cost is then passed down to the consumer in increased utility rates. Failure to increase the capacity of the grid can lead to wide scale blackouts when the energy demand outstrips the supply.

One method to reduce the total demand on the grid during peak hours is by using 'demand response'. Demand response refers to mechanisms that reduce the peak energy demand by moving loads to non-peak periods of the day (shifting) or reducing the total demand during the peak period (shedding). At its most simple, an example of demand response would be to run the domestic household washing machine late in the evening when electricity demand is low. To help reduce peak energy demand and cost, utility companies in the US are beginning to offer tariff-based incentives to consumers. An example of this is *Time of Use* (TOU) schemes where a schedule is set by the utility company offering cheaper energy prices during off-peak times and more expensive energy during peak times. The aim is to encourage consumers to shift their main energy use to periods when energy generation is less expensive and the overall demand may be met more easily.

For the simulations in this report we shall use the 4-hour time periods of 2pm to 6pm for the cooling peak demand period, and 4am to 8am for the heating peak demand period. During these hours, RIVEC will reduce the whole-house ventilation rate in order to reduce the heating/cooling load associated with bringing in ventilation air at these times.

3. THE RESIDENTIAL INTEGRATED VENTILATION CONTROLLER (RIVEC)

The Residential Integrated VEntilation Controller (RIVEC) is a dynamic control system for whole-house ventilation fans. It aims to address the IAQ/energy tradeoff and peak demand problems associated with ventilation, while maintaining compliance with ASHRAE Standard 62.2. RIVEC coordinates the operation of a whole-house exhaust fan in response to other exhaust and supply fans in the house and peak energy demand. It can also lower the ventilation rate when there are high levels of outdoor pollutants, e.g., ozone (ARB, 2005). The system is designed to be used in various climates and programmed according to the house size and number of people in a home.

RIVEC is designed to meet the intent of California's 2012 Title 24 (CEC, 2008) requirements for residential ventilation by compliance with ASHRAE 62.2 (the ventilation standard adopted by Title 24). RIVEC is also designed to manage all compliant residential ventilation systems that the California Energy Commission reviewed in developing the Title 24 requirements. Currently ASHRAE Standard 62.2 only allows the use of intermittent ventilation operating to a *fixed* schedule. This prohibits the use of RIVEC as it operates to a *non*-fixed, adaptive schedule based on IAQ levels and occupancy, so further amendments to the standard are being proposed as a result of the RIVEC work.

Sherman et al. (2009) created and field-tested a prototype of the RIVEC controller in a warm climate (Central Valley, California) in a home with three bathroom fans, a kitchen fan, a dryer exhaust, and an economizer. This field test, reported to the California Energy Commission, demonstrated that the air quality was maintained above the minimum requirement of ASHRAE Standard 62.2

The RIVEC controller is intended to manage any installed whole-house mechanical ventilation system, meeting whole-house ventilation requirements at minimum energy cost. The controller does this by shifting the ventilation load of the whole-house mechanical ventilation system off-peak and taking into account auxiliary mechanical ventilation by other systems (Sherman and Walker, 2011). Other ventilation controllers are available, but unlike RIVEC they do not i) account for the contributions of other systems that mechanically ventilate a home, ii) have the ability to avoid times of peak energy and monetary ventilation cost, or iii) have the capability to track IAQ levels only during occupied hours. To accomplish these three things, the controller must be able to regulate the state of the installed whole-house mechanical ventilation system and sense when all significant exogenous mechanical ventilation systems are operating. For example, if a 75 *L/s* household clothes dryer is running then it is likely that the minimum whole-house ventilation rate will be satisfied by this alone. So the RIVEC-controlled device does not need to operate at the same time (although it can operate at the same time, due to subtle intricacies of the control algorithm). To prevent rapid cycling or switching of the whole-house ventilation fan, the controller makes decisions every 10 minutes (also based on Sherman and Walker (2011)). Note that RIVEC monitors the ventilation devices and performs IAQ calculations on much short timescales, so that short duration fan operation (such as bathroom exhaust fans) can be captured.

To perform the necessary calculations, the controller must be programmed with the following specific house and system parameters:

- Floor area of house
- Volume of house
- Number of bedrooms (a surrogate for the number of occupants)
- Infiltration contribution toward ventilation
- Target ventilation rate in air changes per hour (the first four parameters above are used to calculate this)
- Peak demand hours
- Airflow capacity of the whole-house mechanical ventilation system
- Airflow capacities of each exogenous mechanical ventilation system (e.g. bathroom fans, kitchen range hoods and clothes dryers)

RIVEC uses these inputs in an algorithm to estimate the IAQ for the home relative to that provided by a continuously operating fan that complies with ASHRAE Standard 62.2. The fan controlled by RIVEC must be oversized compared to that specified by ASHRAE 62.2 to compensate for the times while the fan is off.

RIVEC Metrics – Relative Dose and Exposure

The minimum whole-house airflow rate from Equation 1, as specified by ASHRAE Standard 62.2, gives us a fixed target whole-house airflow rate that can be used with an assumed constant pollutant generation rate to calculate occupant exposure to that pollutant. The dynamic controller needs to achieve the same or lower exposure to demonstrate that it achieves equivalent IAQ. ASHRAE 62.2 also requires that kitchens and bathrooms be equipped with exhaust fans that can provide ventilation rates of at least 50 L/s and 25 L/s, respectively. The standard does not specify a minimum operating time for these fans.

It is important to point out the standard is very flexible about how one may achieve the minimum ventilation rate - supply ventilation, exhaust ventilation, balanced ventilation or appropriate combinations thereof may be used. Systems that ventilate incidentally (such as bath fans, clothes dryers, or economizers) may be counted towards the total. RIVEC makes use of this flexibility to improve the energy efficiency of the system.

RIVEC implements the concept of *efficacy* and intermittent ventilation, which allows time shifting of ventilation. Using this approach, ventilation can be shifted away from times of high cost or high outdoor pollution towards times when it is cheaper and more effective.

The intermittent ventilation algorithm in ASHRAE 62.2 is a simplified procedure (that makes it amenable to using tables in the standard), more details of which can be found in Sherman (2006). The RIVEC controller uses the full generalization of that method. The key equations of intermittent ventilation define the efficacy of ventilation as it relates to the pattern of ventilation.

The temporal ventilation effectiveness or efficacy is the ratio of the ventilation one would need if the rate were constant to the actual ventilation. For our simple case it links the equivalent (or desired) steady-state ventilation rate (A_{eq}, which is equivalent to $Q_{62.2}$ plus some infiltration contribution), the actual (or needed) rates of over-ventilation and under-ventilation (A_{high} and A_{low}) and the fraction of time that the space is under-ventilated (f_{low}):

$$\varepsilon = \frac{A_{eq}}{f_{low} A_{low} + (1 - f_{low}) A_{high}} \tag{2}$$

If we have an independent measure of the efficacy, we can use it and Equation 1 to determine the range of acceptable design parameters. The solution is expressed in dimensionless terms involving the efficacy and two other parameters:

$$\varepsilon = \frac{1 - f_{low}^2 \mathrm{N} \cdot \coth(\mathrm{N} / \varepsilon)}{1 - f_{low}^2} \tag{3}$$

where "coth" in Equation (3) is the hyperbolic cotangent and the nominal turn-over, *N*, is defined as follows:

$$\mathrm{N} \equiv \frac{(A_{eq} - A_{low}) \cdot T_{cycle}}{2} \tag{4}$$

where T_{cycle} is the length of a cycle (typically this will be the sum of the time of operation at higher and lower airflows).

We are going to address the case of most interest for peak demand reduction, which is called *Notch Ventilation*. In this case we assume that the ventilation system is shut off for 4 hours per day at times of peak loads or to avoid high concentrations of outdoor pollutants (e.g. ozone) and on continuously for the remaining 20 hours. Using the rates of ASHRAE 62.2 and typical housing values, the efficacy is then 96%. This implies that for the notch ventilation case, we must have a mechanical ventilation system sized 25% larger than if it were being used continuously.

The intermittent ventilation algorithms cited above are based on the effective ventilation work of Sherman and Wilson (1986). In order to generalize the intermittent ventilation rate to ventilation rates that may vary in real time, we need to refer to that work to develop an equivalent way to determine IAQ. We do that by following Sherman and Wilson to determine the equivalent exposure to a general (but constant or uncorrelated) contaminant exposure. For such a case the key parameter is the turn-over time, τ_e:

$$\tau_e(t) = \int_{-\infty}^{t} e^{\int_{t}^{t'} A(t'')dt''} dt' \tag{5}$$

Where *A(t)* is the instantaneous air change rate. If we have a target constant ventilation rate that leads to the appropriate absolute exposure then the *relative exposure*, R, is just the product of that and the instantaneous turn-over:

$$R(t) = A_{eq}\tau_e(t) \tag{6}$$

The intermittent ventilation equations are based on providing the same steady-state dose over any cycle time of interest. The *relative dose, d,* is the average relative exposure over any steady-state cycle, T:

$$d = \frac{1}{T}\int_{0}^{T} R(t)dt = 1/\varepsilon = A_{eq}\bar{\tau} \tag{7}$$

The efficacy used in the intermittent ventilation equations is just then the inverse of the relative dose and can be related to the average turn-over time for the period.

The equations above are useful for continuous unbounded data, but for the purpose of computer simulation it is more useful to use a recursive formula for discrete data. We can rewrite the expression for turn-over time as follows:

$$\tau_i = \frac{1 - e^{-A_i\Delta t}}{A_i} + \tau_{i-1}e^{-A_i\Delta t} \tag{8}$$

We can also write an expression for the (recursive) discrete relative dose based on a 24-hour control cycle. This value varies only a few percent from unity for notch ventilation.

$$d_i = A_{eq}\tau_i(1 - e^{-\Delta t/24hrs}) + d_{i-1}e^{-\Delta t/24hrs} \tag{9}$$

The RIVEC control algorithm determines when to turn the whole house fan on and off to maintain a relative dose of unity and control relative exposure extremes.

Occupied Relative Dose and Exposure

While the household occupants are absent they are no longer being exposed to the indoor contaminants of the home. This requires slight modifications to how we calculate the relative dose and exposure, or rather, the *occupied* relative dose and exposure. As relative exposure is governed by pollutants significant over acute time periods, when the occupant is absent the occupied relative exposure simply drops to zero. The relative exposure levels in the house must continue to be tracked by RIVEC so that the appropriate level of relative exposure can be calculated for when the occupants return. However, as relative dose deals with pollutants significant over chronic time periods, the calculations need to account for the periods when the occupants are absent. Equation (9) for the relative dose at time i is based on the relative dose at time $i-1$ and the current relative exposure. For unoccupied times, unity is used instead of the actual relative exposure:

$$d_{unoccupied,i} = 1 \cdot \left(1 - e^{-\frac{\Delta t}{24hrs}}\right) + d_{unoccupied,i-1} e^{-\frac{\Delta t}{24hrs}} \tag{10}$$

When the building is occupied once more the dose calculation returns to normal using Equation (9).

RIVEC Control Algorithm

The RIVEC control algorithm was first outlined by Sherman and Walker (2011) and Sherman et al. (2009). This work further develops the control algorithm in response to the results and recommendations from those reports. The main modifications are to eliminate the pre-peak and post-peak shoulder periods, to remove minimum and maximum ventilation rates and to include occupancy sensing. These measures were implemented to both simplify the control algorithm and make it more robust for a larger range of houses with different ventilation strategies in different climates.

The new algorithm recognizes only two time periods - a peak energy demand period and a non-peak energy demand period (i.e. normal operation). During normal operation the whole-house ventilation strategy is controlled by an upper limit to the relative exposure and the relative dose. The values of these upper limits depend on the occupancy of the house. When the house is occupied, the relative exposure is limited to a maximum of 0.95 and the relative dose is limited to a maximum of 1.0. The relative exposure maximum of 0.95 was a conservative choice intended to protect IAQ. If the dose and exposure are less than these values the RIVEC controller switches off the ventilation device. This decision is made by the controller every 10 minutes. As soon as either of these values has been exceeded, the ventilation device is switched back on. During unoccupied periods the algorithm controls operation of the whole-house fan based on a limit to the relative exposure only (based on Sherman et al. (2011b)), R_{lim}, defined by:

$$R_{lim} = 1 + 4 \cdot \left(\frac{1 - X}{1 + Y} \right) \tag{11}$$

Where:

$$X = \frac{Q_{62.2}}{Q_{RIVEC}} \tag{12}$$

$$Y = \frac{Q_{infiltration}}{Q_{RIVEC}} \tag{13}$$

$Q_{62.2}$ [L/s] is the minimum whole-house ventilation airflow rate as defined by ASHRAE Standard 62.2, defined in Equation 1. Q_{RIVEC} [L/s] is the airflow rate of the RIVEC-controlled fan. $Q_{infiltration}$ [L/s] is the infiltration contribution toward ventilation i.e., the default infiltration credit (see below).

R_{lim} is a function of the size of the RIVEC fan, and will have a larger value than the 0.95 relative exposure limit imposed during occupied periods. The larger value for R_{lim} allows the ventilation device to be off for longer periods while the house is unoccupied, as the inhabitants will not be exposed to the higher levels of indoor contaminants, while limiting the peak levels that a returning occupant is exposed to at the beginning of the occupancy period. Previous work by Sherman and Walker (2011) has shown that a fan sized to 125% of the ASHRAE 62.2 minimum ventilation rate is required for a fan that will be switched off for at least four hours every day (the peak energy demand period).

During the peak energy demand period the RIVEC controller switches off the ventilation device. It will only turn back on if the relative exposure exceeds the above exposure limit, R_{lim}. The peak periods are hardcoded into the controller. For this study, 4 am until 8 am was used for heating days and 2 pm until 6 pm was used for cooling days. As both heating and cooling set points were used to control the furnace and the air-conditioning, there were occasions when both heating and cooling occurred on the same day. The RIVEC algorithm allows for only one peak period on these days in order to avoid the situation where the ventilation system would be off for two four-hour periods (eight hours total) in any 24-hour period, causing high levels of indoor contaminants.

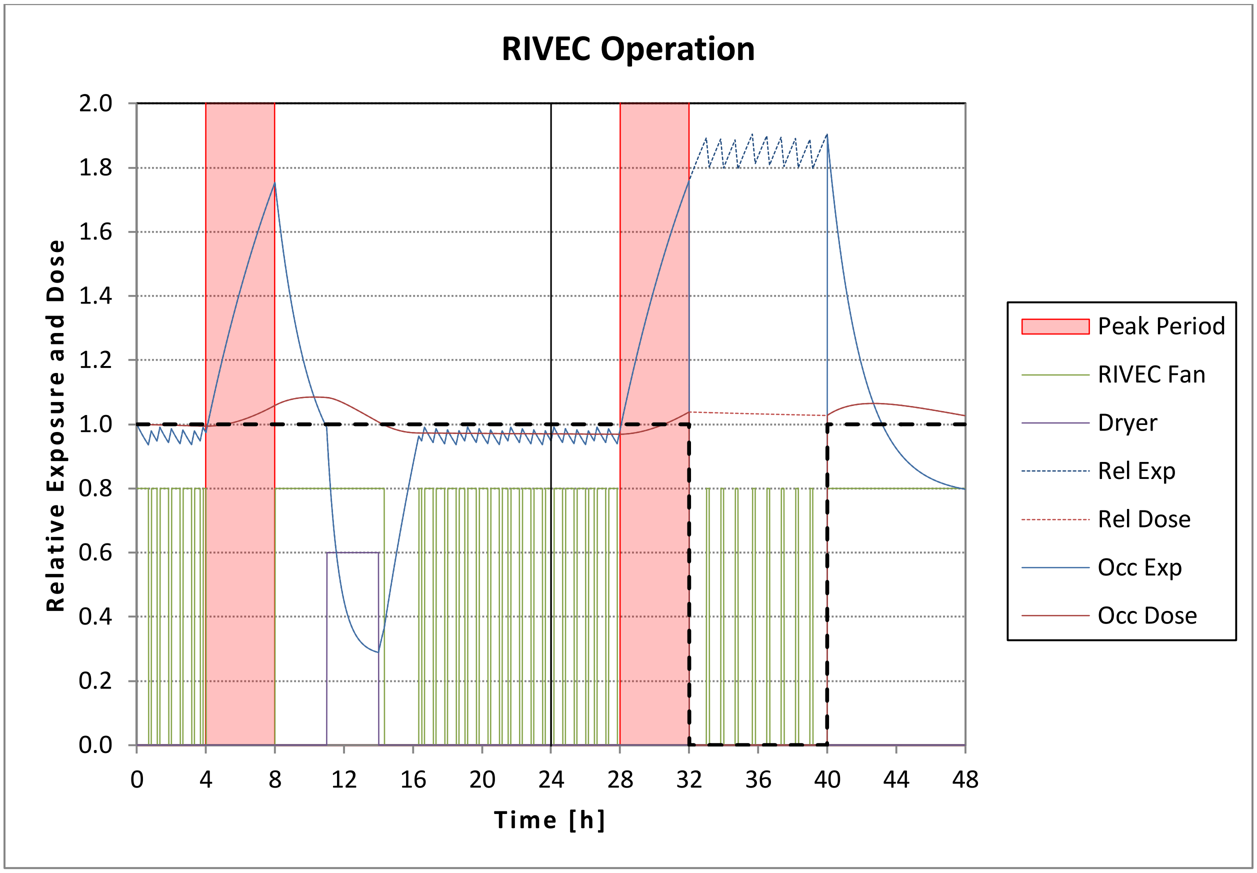


Figure 1: Relative Dose and Exposure controlled by RIVEC, accounting for dryer operation

Figure 1 illustrates an example of RIVEC operation over a 48-hour period. During the occupied period (shown by the dashed black line, where 1.0 = occupied and 0 = unoccupied), the relative dose is limited to 1.00 and relative exposure is limited to 0.95 by cycling the RIVEC fan (green line). Between 4am and 8am (the peak heating energy period shown by the shaded red region) the RIVEC fan is switched off and the dose and exposure rise. The RIVEC fan will not turn back on unless the relative exposure limit (R_{lim}) is exceeded, or the peak period ends. Once the peak period is over, the RIVEC fan turns back on and runs continuously to bring the dose and exposure back down to the specified limit values. On day 1, the clothes dryer (purple line) turns on at 11am and runs for three hours. The RIVEC controller senses the dryer operation and accounts for the effect of the additional ventilation on the dose and exposure. Thus, the RIVEC controller turns off the whole-house RIVEC fan sooner than if the dryer had not been operated. During the unoccupied period on day 2, the occupied relative exposure drops to zero and the occupied relative dose remains constant. The relative exposure is controlled at the exposure limit given by Equation (11). When the occupants return at the end of the working day, the occupied relative exposure and dose return to the levels of the relative exposure and dose. For the two-day period, the RIVEC fan operates for 1,630 minutes i.e. 57% of the time, as opposed to 100% for a continuously operating fan.

Meeting Chronic and Acute IAQ Levels with Intermittent Ventilation

Logue et al. (2010) determined that $PM_{2.5}$, formaldehyde, and NO_2 were the most significant indoor contaminants with respect to human health impacts over acute timescales. Sherman et al. (2011a) then presented a methodology for assessing the viability of intermittent whole-house ventilation strategies to meet ASHRAE Standard 62.2 by analyzing relative indoor pollutant concentrations of contaminants thought to be important over short-term, acute timescales (Table 1). In the context of this study, the lowest acute-to-chronic ratio represents the maximum relative exposure allowed from an IAQ perspective. From Table 1, the maximum relative exposure levels were outlined for 1, 8 and 24-hour time periods of 4.7 (NO_2), 5.4 (Formaldehyde) and 2.5 ($PM_{2.5}$) respectively). For timescales the order of a few hours (i.e. 1 to 8 hours), the relative exposure is the appropriate metric and it should not exceed 4.7 for NO_2 or 5.4 for Formaldehyde. The relative dose is calculated as a 24-hour running average of the relative exposure, so this is the appropriate metric that should not exceed 2.5 - the 24-hour acute-to-chronic ratio for $PM_{2.5}$.

Table 1: Maximum concentrations of hazardous indoor contaminants allowed by standards and guidelines (Sherman et al., 2011)

Concentration [μg/m³]				
COMPOUND	**Chronic**	**Acute**		
		24 h	**8 h**	**1 h**
Acetaldehyde*	3.70E+00	-	3.00E+02	4.70E+02
Acrolein*	2.00E-02	-	7.00E-01	2.50E+00
Acrylonitrile	3.00E-02	-	-	-
Benzene*	3.40E-01	-	-	1.30E+03
Benzyl Chloride	2.00E-01	-	5.17E+03	2.40E+02
Butadiene, 1,3-*	6.00E-02	-	-	-
Cadmium	2.40E-03	-	-	-
Carbon Tetrachloride	2.40E-01	-	-	1.90E+03
Chloroform	1.98E+00	-	-	1.50E+02
Chromium	6.70E-05	-	-	-
Dichlorobenzene, 1,4-*	9.10E-01	-	4.50E+04	-
Dichloropropane,1,2-	4.00E+00	-	3.50E+05	-
Ethanol	-	-	1.90E+06	-
Ethylbenzene	4.00E+00	-	-	-
Formaldehyde*	**1.67E+00**	-	**9.00E+00**	5.50E+01
Hexachlorobutadiene	4.50E-01	-	-	-
Methylene Chloride	1.00E+01	-	-	1.40E+04
Naphthalene*	2.90E-01	-	5.00E+04	-
NO2*	**4.00E+01**	-	-	**1.89E+02**
PM2.5*	**1.00E+01**	**2.5E+01**	-	-
Tetrachloroethane, 1,1,2,2-	1.70E-01	-	3.50E+04	-
Tetrachlorothene	1.69E+00	-	-	2.00E+04
Vinyl Chloride	1.30E-01	-	-	1.80E+06
Lowest Acute-to-Chronic Ratio [-]	**-**	**2.5**	**5.4**	**4.7**

** Compounds identified as key contaminants (Logue et al., 2010).*

Infiltration Credit

The 2010 edition of ASHRAE Standard 62.2 has a default infiltration credit of 10 L/s per 100 m^2 (2 cfm/100 ft^2) of floor space. This infiltration credit is used to reduce the installed mechanical fan airflow requirements for the whole-house ventilation system. It does not apply to local exhaust ventilation.

The RIVEC controller cannot sense the contribution of infiltration towards ventilation, but this contribution still needs to be accounted for in the calculations. In this study we used the ASHRAE 62.2 2010 approach of including the default infiltration credit of 10 L/s per 100 m^2 ($Q_{infiltration}$ in Equation 11) in the target whole-house ventilation rate (A_{eq}). This was to allow easy comparison with the existing ASHRAE 62.2 standard. Consequently, we used the default infiltration credit as a baseline ventilation rate in the RIVEC calculations for the simulations.

Addendum N to ASHRAE 62.2 has recently been published. It revises the standard to:

- explicitly include the default in the total airflow requirements
- include the full infiltration credit (rather than the current half-credit)
- update the climate-dependent weather factors, *w*, (including adding many hundreds more weather stations), and
- move all the required calculations into Standard 62.2 thus eliminating the references to Standards 119 and 136.

The difference between the old ASHRAE 62.2 method and new Addendum N in terms of total ventilation rate is usually small, but tighter homes will require more mechanical ventilation.

To bring RIVEC in-line with Addendum N, it is envisaged that the RIVEC controller will have a preprogrammed look-up table that will allow the commissioning agent to set the appropriate ventilation credit by selecting a building envelope leakage and weather factor *w*, depending on where the house is located. The infiltration credit will be a fixed value independent of local fluctuations in the weather data.

4. WHOLE-HOUSE MECHANICAL VENTILATION STRATEGIES

This study simulates the operation of four mechanical residential whole-house ventilation strategies:

1. Whole-house exhaust fan
2. Heat Recovery Ventilator (HRV)
3. Central Fan Integrated Supply (CFIS) combined with a whole-house exhaust fan
4. Air-side economizer combined with a whole-house exhaust fan

These are ventilation systems typically found in new homes that are ASHRAE 62.2 compliant. For this study, simulations were conducted with and without RIVEC incorporated into the systems to assess the performance of RIVEC at reducing ventilation energy costs while attempting to maintain IAQ.

Strategy 1: Whole-House Exhaust

In this system the primary whole-house ventilation system is a simple exhaust fan (Figure 2). When the exhaust fan operates it depressurize the house. Outside air is drawn in through cracks, leaks and openings in the building envelope. In the default configuration, the fan runs continuously at the minimum rate specified by ASHRAE Standard 62.2.from Equation 1. Under RIVEC operation, RIVEC turns the whole-house exhaust fan on or off.

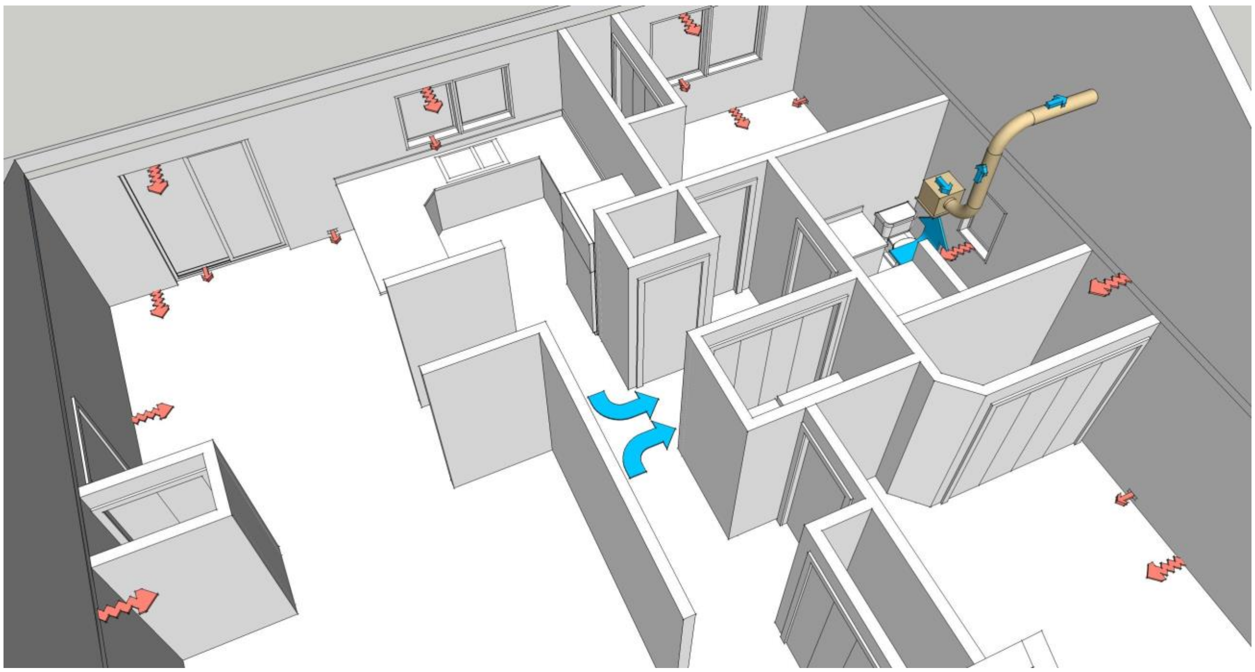


Figure 2; Mechanical whole-house exhaust system. Blue arrows indicate conditioned air; red arrows indicate unconditioned air. In this figure the whole-house exhaust is located in the bathroom.

Strategy 2: Heat Recovery Ventilator (HRV)

An HRV is a balanced ventilation system provides heat recovery from the outgoing air to the incoming air using an air-air heat exchanger (Figure 3). The most common installation, and the one we simulated, has the HRV sized significantly larger than that specified by the ASHRAE 62.2 rate (we simulated a factor of 2 larger), and integrated with the forced air system and ductwork. The HRV and the air handler are synchronized. In the default configuration, both cycle every 30 minutes on a timer to meet the ASHRAE 62.2 minimum airflow rate (ASHRAE 62.2 permits intermittent whole-house ventilation so long as it is to a fixed schedule. Under RIVEC operation, RIVEC controls when the HRV is on and when it is off.

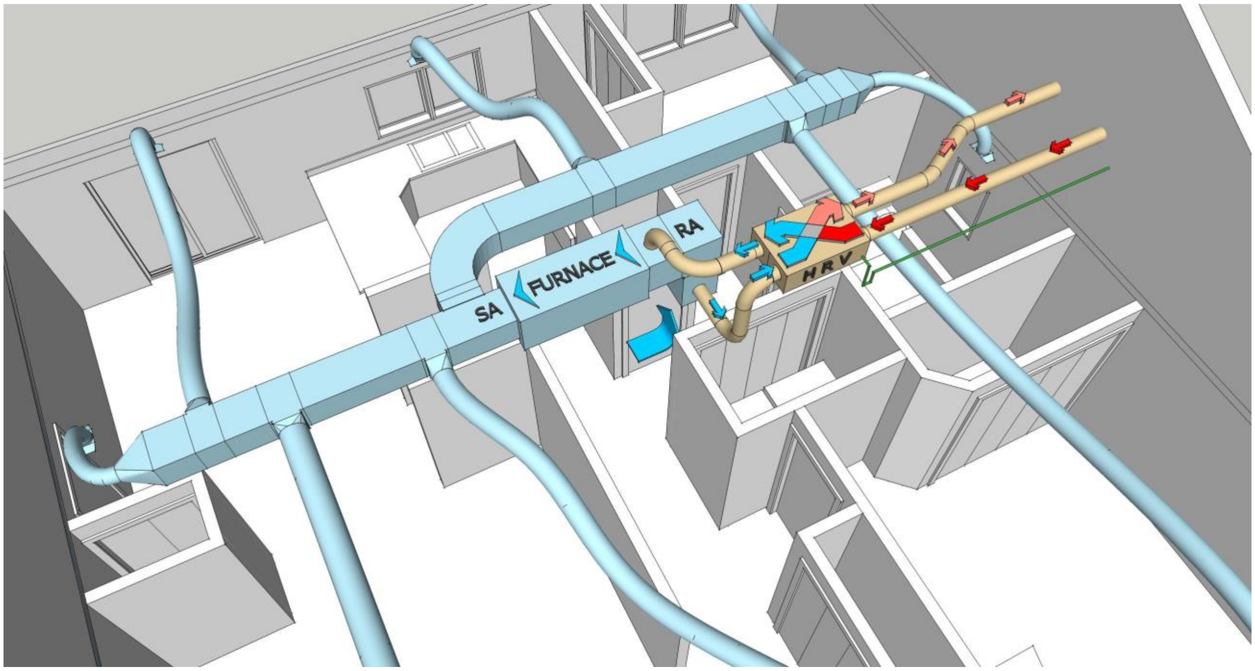


Figure 3: Heat Recovery Ventilator system fully integrated in the forced air system

Strategy 3: Central Fan Integrated Supply (CFIS) with Whole-House Exhaust

CFIS uses the air handler to draw outside air into the return via a duct to outside (Figure 4). The outside air is mixed with the return air from the forced air system and distributed throughout the house using the heating/cooling ducts. A damper in the outside air duct opens automatically during air handler operation for heating or cooling. The outside air damper is sized so that when the air handler is operating, the airflow rate from outside meets the ASHRAE Standard 62.2 continuous rate. Because this system does not operate continuously, nor intermittently to a fixed schedule, it is not ASHRAE 62.2 compliant and so not controlled by RIVEC. To comply with 62.2, the system must operate in conjunction with a continuously operating whole-house exhaust fan. In the default configuration, the whole-house exhaust fan operates continuously. Under RIVEC, operation the whole-house fan is controlled by RIVEC.

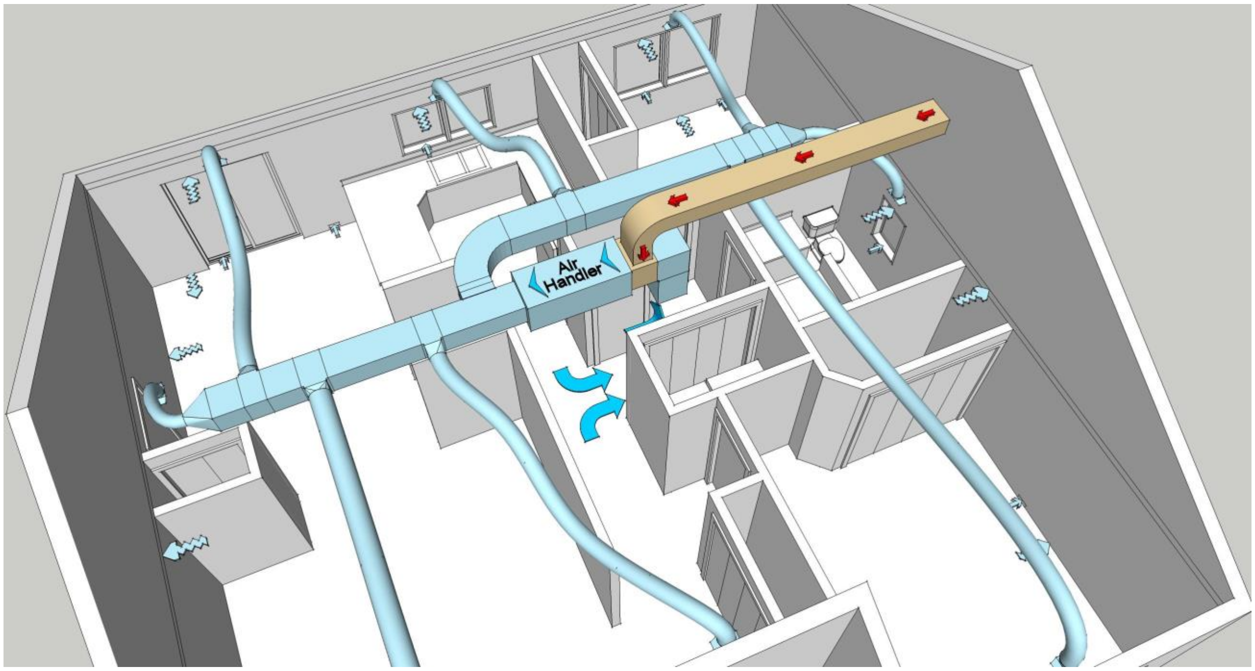


Figure 4: Central Fan Integrated Supply system

Strategy 4: Economizer with Whole-House Exhaust

In the context of this study, economizers are large supply fans that reduce the cooling load of a building by supplying cool nighttime air to the occupied zone in climates with large diurnal temperature swings. In typical residential applications, the heating/cooling air handler is used as the economizer fan. A damper opens allowing the economizer to distribute outside air to the occupied zone via the supply ducts. During operation of the economizer, a pressure relief opens in the ceiling to avoid pressurizing the house.

Economizers are used to provide cooling to the house. The ventilation they provide from the increased airflow rates is incidental and also climate-dependent. For this reason the economizer system is combined with a whole-house exhaust fan in order to comply with ASHRAE 62.2. Under the default configuration the whole-house exhaust operates continuously. Under RIVEC operation, the whole-house fan is controlled by RIVEC. RIVEC takes into account the effect on IAQ when the economizer operates, and delays the use of the whole-house exhaust appropriately.

Exogenous Mechanical Ventilation

In a single house there may be only one whole-house system designed and controlled to meet minimum ventilation requirements. However, other pieces of equipment in the house can have significant impacts on the total mechanical ventilation rate. The RIVEC controller monitors many of these exogenous systems (currently using wireless transmitters that signal to RIVEC when the fan is on or off) and accounts for their impacts on IAQ, thereby decreasing the need for additional mechanical ventilation.

The systems that RIVEC can monitor include:

- clothes dryers - according to ASHRAE 62.2 and building codes, clothes dryers must be vented to outside. When the dryers operate, this venting alone is usually sufficient to meet minimum whole-house requirements and thus it may be possible to turn off the whole-house ventilation system when the dryer is operating

- bathroom extract fans – used to control odor and moisture generated in bathrooms. ASHRAE 62.2 prescribes that intermittently operating bathroom fans should have a minimum flow rate of 25 L/s (50 cfm)

- kitchen range hoods – used to control cooking generated indoor pollutants. ASHRAE 62.2 prescribes that intermittently operating kitchen range hoods should have a minimum ventilation rate of 50 L/s (100 cfm).

Households use these fans in different ways, and so their operation needs to be monitored in real-time by RIVEC. Due to their high flow rates, they can provide significant ventilation while running. Each of the four whole-house ventilation strategies simulated in this study also included the operation of clothes dryers, bathroom exhaust fans and kitchen range hoods.

5. SIMULATIONS

Five different residential ventilation strategies were simulated (Table 2). All of the strategies include the exogenous ventilation described above. Each ventilation strategy was simulated for three house sizes, three envelope leakage values, and in 13 U.S. climates.

Strategy 'zero' is a reference case with no whole-house ventilation system operating. It acts as a baseline for all other cases so that the ventilation energy can be calculated, i.e. the extra energy incurred from adding whole-house ventilation to a home.

Strategies 1 (whole-house exhaust), 3 (CFIS), and 4 (economizer) all had whole-house exhaust fans that were simulated either running continuously (1a, 2a, 4a) or under RIVEC control (1b, 2b, 4b). Strategy 2 (HRV) operated for either the first 30 minutes of every hour (3a), or under RIVEC control (3b).

Table 2: Simulations for the different ventilation strategies (exogenous ventilation systems operate for all strategies)

Strategy #	Ventilation System	Simulations
0.	**No whole-house ventilation system**	'Zero' case to be used as a reference for adding whole-house ventilation
1.	**Whole-House Exhaust Fan** • sized to meet the 62.2 minimum airflow rate	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control
2.	**Heat Recovery Ventilation (HRV)** • sized to twice the 62.2 minimum airflow rate	HRV operates: a. for 30 minutes every hour b. intermittently under RIVEC control
3.	**Central Fan Integrated Supply (CFIS)** • with airflow sized to meet 62.2 • operates whenever the heating or cooling system operates • combined with 62.2 whole-house exhaust fan	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control
4.	**Economizer** • using the air handler operating at cooling fan power and airflow rate • combined with 62.2 compliant whole-house exhaust fan	Whole-house exhaust fan operates: a. continuously b. intermittently under RIVEC control

Building Simulation Tool

The energy consumption and IAQ of the modeled houses was evaluated by time resolved simulations of the heat and mass balances of the home for a year. The airflows, heat transfer, heating and cooling system operation and energy use were simulated using the REGCAP residential building simulation tool that has been used in previous studies on RIVEC (Walker and Sherman, 2008, Sherman and Walker, 2008). The simulation tool has been validated by comparison to measured data in homes in previous studies (Walker et al., 2006). The simulation program treats the attic volume and house volume as two separate well-mixed zones but connected for airflow and heat transport, and includes heating and cooling system airflows. It combines mass transfer, heat transfer and moisture models. The program allows the modeling of distributed envelope leakage and mechanical system airflows for ventilation, heating and cooling, as well as individual localized leaks. Inputs are building air leakage characteristics (total leakage and leakage distribution), time resolved weather data, weather shielding factors, building and HVAC equipment properties, and auxiliary fan schedules. Simulations were performed with a one-minute time resolution.

Climates

IECC climate zones 2A to 7 (Briggs et al., 2003) were used in the simulations (see Figure 5 and Table 3). Economizer operation is thought to be inadvisable in humid climates and so was not simulated in the moist 'A' climates. Weather data was taken from the TMY3 dataset published by NREL (Wilcox and Marion, 2008). TMY3 is hourly data so this was converted to the one-minute resolution needed for use in REGCAP using linear interpolation. The weather data used as input for the simulation modeling was:

- direct solar radiation [W/m^2]
- total horizontal solar radiation [W/m^2]
- outdoor air dry-bulb temperature [°C]
- outdoor air humidity ratio [g/kg]
- wind speed [m/s]
- wind direction [degrees]
- barometric pressure [kPa]
- cloud cover index [-]

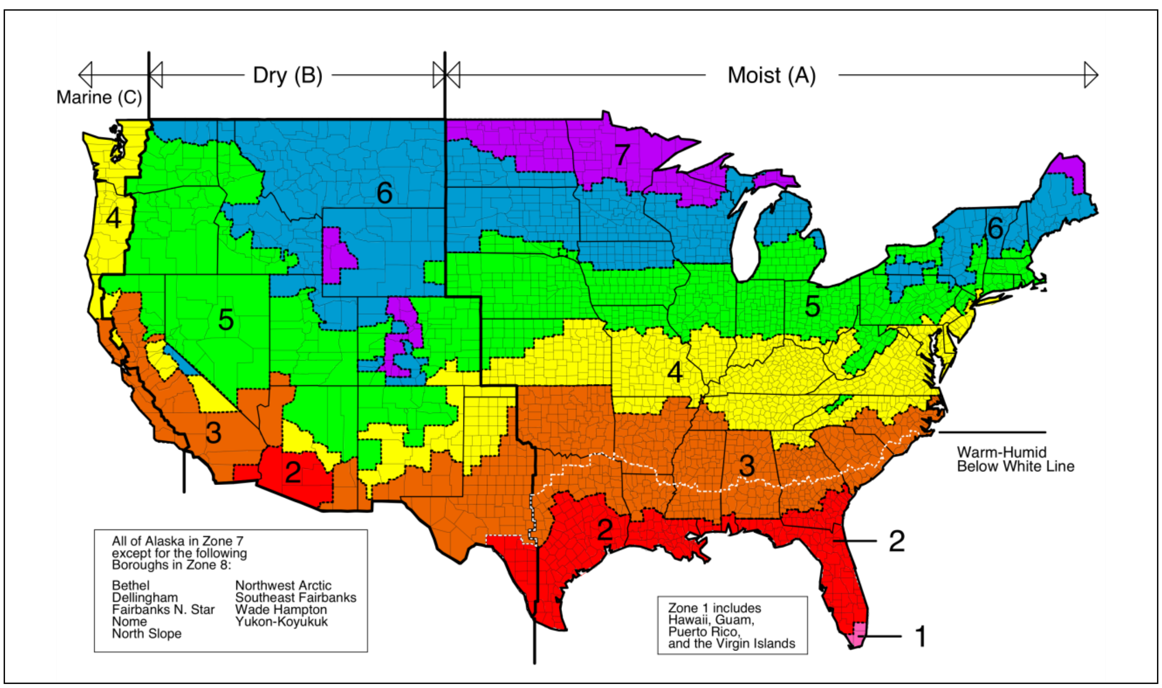


Figure 5: Map of the IECC US climate zones

Table 3: IECC Climate Zones with definitions (Briggs et al., 2003)

Climate Zone	Representative City	State	Temp	Moisture	Köppen Classification Description
2A	Houston	TX	Hot	Humid	Humid Subtropical (Warm Summer)
2B	Phoenix	AZ	Hot	Dry	Arid Subtropical
3A	Memphis	TN	Warm	Humid	Humid Subtropical (Warm Summer)
3B	El Paso	TX	Warm	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
3C	San Francisco	CA	Warm	Marine	Dry Summer Subtropical (Mediterranean)
4A	Baltimore	MD	Mixed	Humid	Humid Subtropical/Humid Continental (Warm Summer)
4B	Albuquerque	NM	Mixed	Dry	Semiarid Middle Latitude/Arid Subtropical/Highlands
4C	Salem	OR	Mixed	Marine	Marine (Cool Summer)
5A	Chicago	IL	Cool	Humid	Humid Continental (Warm Summer)
5B	Boise	ID	Cool	Dry	Semiarid Middle Latitude/Highlands
6A	Burlington	VT	Cold	Humid	Humid Continental (Warm Summer/Cool Summer)
6B	Helena	MT	Cold	Dry	Semiarid Middle Latitude/Highlands
7	Duluth	MN	Very Cold	-	Humid Continental (Cool Summer)

House Size

Three different houses (see

Table 4) were simulated to give a good representation of the majority of the housing stock in the US. The medium and large houses were based on the CEC's Title 24 prototype simulation houses (Nittler and Wilcox, 2008) Prototype C (see Figure 6) and Prototype D. The small house is a scaled down version of Prototype C. For the purposes of this report, the small house shall be referred to as Prototype B. All houses had uniform 2.5 m (8 ft) ceilings on each floor. While the modeling tool used does not specifically allow for an attached garage, the presence of a garage was accounted for in the building geometry, i.e. the building perimeter lengths and floor areas where adjusted appropriately.

Table 4: Simulation houses and their properties

Name	House Size	Floor Area [m^2]	Floor Area [ft^2]	Stories	Bedrooms	Bathrooms	Occupants
Prototype B	Small	111	1,200	1	3	2	4
Prototype C	Medium	195	2,100	1	3	3	4
Prototype D	Large	250	2,700	2	4	3	5

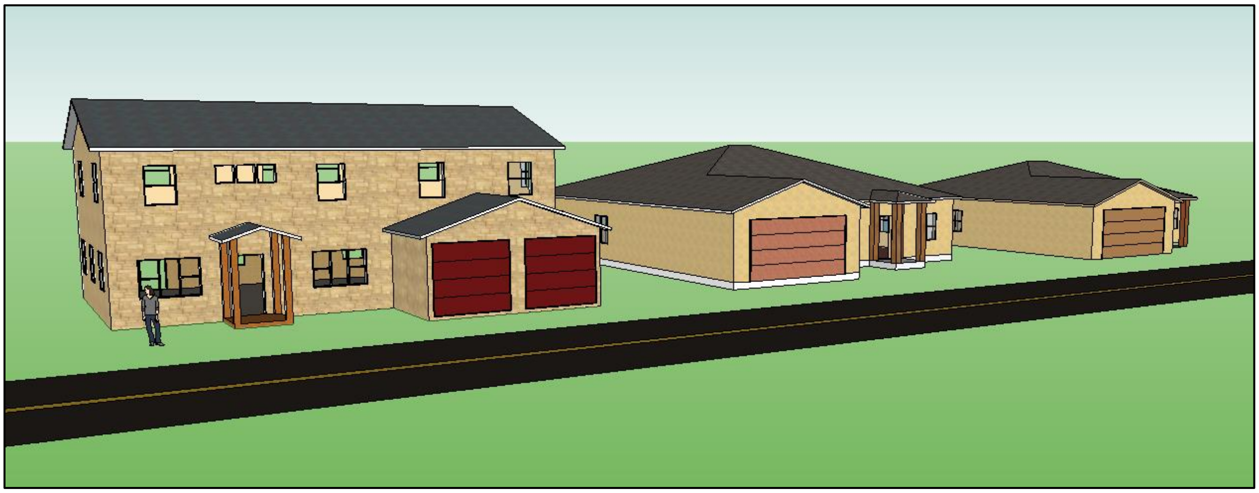


Figure 6: The simulation houses from right to left – Prototypes B, C and D

House Construction and Envelope Leakage

Each house was simulated with three different envelope leakages. Recent studies by Offerman (2009) and Wilcox (2011) have shown that 4.8 ACH_{50} is typical of new construction homes. Simulations were also performed with envelope leakages of 2.0 ACH_{50} to represent tight home and 8.0 ACH_{50} to represent older, leakier homes.

Leakage distribution was one-quarter in the floor, one-quarter in the ceiling, and half in the walls. The house had no open flues, fireplaces or windows. The garage was omitted from the simulations and treated as outside, unconditioned space.

Insulation and Fenestration

R-Values of walls and ceilings, U-Factors and Solar Heat Gain Coefficients (SHGC) for windows were based on the IECC 2009 values. House insulation used to determine the non-ventilation building load varied by climate (see

Table 5).

Table 5: House Insulation Levels from IECC 2009 Table 402.1.1

Climate Zone	Representative City	Glazing		Ceiling	Walls	Ducts Outside Conditioned Space
		U	SHGC			
2A	Houston, TX	0.65	0.3	R30	R13	R8
2B	Phoenix, AZ	0.65	0.3	R30	R13	R8
3A	Memphis, TN	0.50	0.3	R30	R13	R8
3B	El Paso, TX	0.50	0.3	R30	R13	R8
3C	San Francisco, CA	0.50	0.3	R30	R13	R8
4A	Baltimore, MD	0.35	0.3	R38	R13	R8
4B	Albuquerque, NM	0.35	0.3	R38	R13	R8
4C	Salem, OR	0.35	0.3	R38	R20	R8
5A	Chicago, IL	0.35	0.3	R38	R20	R8
5B	Boise, ID	0.35	0.3	R38	R20	R8
6A	Burlington, VT	0.35	0.3	R49	R20	R8
6B	Helena, MT	0.35	0.3	R49	R20	R8
7	Duluth, MN	0.35	0.3	R49	R21	R8

The exterior surface area for wall insulation scales with floor area and number of stories. The total building surface area is typically three times the floor area (based on the BSC/Building America data set). A simple rule of thumb developed from measured data from several thousand new homes and from the simplified Title 24 Prototype C in the Alternative Compliance Manual is that the wall area is typically 1.22 times the floor area for a one-story home. Total window area was 20% of the floor area, with the windows equally distributed between North, South, East and West. Clear glazing was simulated with exterior shading of 50%. The houses had Northerly facing doors with an area of 3.7 m^2 (40 ft^2) and a U-Factor of 0.50.

Internal Loads

Internal latent loads increase indoor humidity and depend on occupant activities. The daily latent gain from moisture generation followed the approach used previously by Walker and Sherman (2006) and Walker and Sherman (2007). The moisture generation rates are based on ASHRAE Standard 160 (ASHRAE, 2009) with corrections for kitchen and bathroom generation from Emmerich et al. (2005) (see Table 6). All of the kitchen and bathroom generated moisture was assumed to be vented directly to outside using exhaust fans.

The daily sensible gain (heat exchange that results in a change in temperature) from lights, appliances, people and other sources used the Title 24 ACM value of 5.9 kWh/day (20,000 Btu/day) for each dwelling unit, plus 0.0044 kWh/day (15 Btu/day) for each square foot of conditioned floor area. For the simulation houses, this translates to a sensible load of 630 W and a moisture net generation rate of 9.8

kg/day. These internal loads were delivered to the occupied zone at a constant rate throughout the day and were not altered for seasonal adjustments.

Table 6: Internal occupancy based moisture generation rates from ASHRAE Draft Standard 160P

Number of Occupants	Moisture Generation Rate [kg/day]	Bathing, Cooking and Dishwashing [kg/day]	Net Generation Rate [kg/day]
2	7.8	3.2	4.6
3	12.1	3.6	8.5
4	13.8	4.0	9.8
5	14.7	4.4	10.3

HVAC Equipment

The details of the heating, cooling and mechanical ventilation systems used in the simulations are listed below.

Heating and Cooling

Heating and cooling equipment was sized according ACCA Manuals J & S (ACCA, 2006). For heating we used a minimally efficient 80% AFUE natural gas furnace. For cooling, we used a SEER 13 split-system air conditioner with a TXV refrigerant flow control. Heating and cooling ducts were located in the unconditioned attic. The total duct leakage was 6%, evenly split between 3% supply leakage and 3% return leakage.

Field studies by Walker (2008), Proctor and Parker (2000) (245 systems) and Philips (1998) (71 systems) have shown that existing fans in residential Permanent Split Capacitor air handlers (which are the most common) typically draw 500W or more and supply airflow at approximately 2 cfm/W.

Thermostat Set Points

Table 7 shows the thermostat set points used in the simulations for the heating and cooling equipment. We used a pre-programmed, automatic thermostat with set-point temperatures that depended on the time-of-day.

Table 7: Thermostat Set Points

Time		Heating		Cooling	
Start	End	°C	°F	°C	°F
0:00	1:00	20.0	68	25.0	77
1:00	2:00	20.0	68	25.0	77
2:00	3:00	20.0	68	25.0	77
3:00	4:00	20.0	68	25.0	77
4:00	5:00	20.0	68	25.0	77
5:00	6:00	20.0	68	25.0	77
6:00	7:00	20.0	68	25.0	77
7:00	8:00	21.1	70	26.7	80
8:00	9:00	21.1	70	26.7	80
9:00	10:00	21.1	70	26.7	80
10:00	11:00	21.1	70	26.7	80
11:00	12:00	21.1	70	26.7	80
12:00	13:00	21.1	70	26.7	80
13:00	14:00	21.1	70	26.7	80
14:00	15:00	21.1	70	26.7	80
15:00	16:00	21.1	70	26.7	80
16:00	17:00	21.1	70	25.0	77
17:00	18:00	21.1	70	25.0	77
18:00	19:00	21.1	70	25.0	77
19:00	20:00	21.1	70	25.0	77
20:00	21:00	21.1	70	25.0	77
21:00	22:00	21.1	70	25.0	77
22:00	23:00	21.1	70	25.0	77
23:00	0:00	20.0	68	25.0	77

Ventilation Equipment

The simulated houses were designed to have ventilation systems that complied with ASHRAE Standard 62.2. The modeled ventilation systems had to meet a whole-house ventilation rate based on the combination of natural infiltration and mechanical ventilation. Thus, the target ventilation rate (Q_{eq}) for demonstrating equivalence to ASHRAE 62.2 is the sum of $Q_{62.2}$ (the mechanical component from Equation 1) and the default infiltration credit Q_{infil} (the assumed natural ventilation component):

$$Q_{eq} = Q_{62.2} + Q_{\inf} \tag{14}$$

Q_{inf} is equal to 10 L/s per 100 m^2 (2 cfm/100 ft^2) in the 2010 edition of ASHRAE Standard 62.2. Q_{eq} is then converted into air changes per hour for use as A_{eq} in the relative dose and exposure calculations (see RIVEC Metrics – Relative Dose and Exposure, above).

The whole-house RIVEC fan airflow rates Q_{RIVEC} need to be 25% larger than $Q_{62.2}$ (not including the default infiltration credit) to account for the four-hour long peak periods when the fan is forced to be off. These airflow rates are summarized in Table 8.

Table 8: Simulation airflow rates for the three test houses

House	Floor Area		Bedrooms	Mechanical Target, $Q_{62.2}$		Infiltration Credit, Q_{inf}		Required Whole-House Airflow Rate, Q_{eq}		RIVEC Fan Airflow Rate, Q_{RIVEC}	
	[m^2]	[ft^2]		[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]	[L/s]	[cfm]
Prototype B	111	1,200	3	20	42	11	24	31	66	25	53
Prototype C	195	2,100	3	24	51	20	42	44	93	30	64
Prototype D	250	2,700	4	30	65	25	54	55	119	38	81

All of the ventilation equipment used in the simulations (see

Table 9) was taken from the Home Ventilating Institute 2011 Directory (HVI, 2011) and was 62.2 compliant. Note that some fans are multispeed and can be used to provide more than one airflow rate. The fans met the sound and installation requirements of 62.2. From an energy use perspective, the main effect is that fans that meet the 1.0 sone requirement for continuous operation (and 3.0 sone for intermittent operation) tend to be energy efficient fans.

Table 9: Ventilation equipment for the different simulation houses (HVI, 2011)

House	System	Equipment	Q [L/s]	Q [cfm]	Power [W]	ASE [-]
Prototype B (Small)	Whole-House Fan	*Panasonic FV-08VKM2*	24	50	10.2	-
	RIVEC Fan	*Panasonic, FV-08VKS2*	28	60	11.8	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*N/A*	71	150	-	-
	HRV	*VENMAR - AVS Constructo 1.5V*	40	85	64	75
Prototype C (Medium)	Whole-House Fan	*Panasonic, FV-08VKS2*	28	60	11.8	-
	RIVEC Fan	*Panasonic, FV-08VKS2*	33	70	14	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*N/A*	71	150	-	-
	HRV	*GREENTEK - DH 7.15*	56	119	114	75
Prototype D (Large)	Whole-House Fan	*Panasonic, FV-08VKS2*	33	70	14	-
	RIVEC Fan	*RenewAire V80*	39	80	16.1	-
	Kitchen Range Hood	*Venmar ESV1030BL*	47	100	37.2	-
	Bathroom Exhaust	*Panasonic FV-08VKM2*	24	50	10.2	-
	Clothes Dryer	*N/A*	71	150	-	-
	HRV	*BROAN-NUTONE - Maytag*	65	138	124	72

Whole-House Exhaust Fans and RIVEC Fans

The whole-house exhaust fan was sized to meet the ASHRAE 62.2 minimum for all the systems that incorporated a fan. A fan was then chosen from the HVI Directory that met this requirement. As commercially-available fans in the US are usually sized to a round number in cfm, some of the whole-house fans had airflow rates that were slightly larger than the 62.2 whole-house minimum. The same applies to the RIVEC fans which were sized to be at least 125% of the 62.2 whole-house minimum. When not under RIVEC control the whole-house exhaust fans operated continuously (Strategies 1a, 3a, and 4a). Under RIVEC control the fans operated intermittently (Strategies 1b, 2b, and 4b)

Heat Recovery Ventilators

A typical application of an HRV system was assumed, where the HRV was connected to the central forced air duct system. The air handler was operated at the same time as the HRV for air distribution and to avoid short-circuiting of ventilation air. The HRV unit was sized to twice the 62.2 airflow rate and then operated on a timer for 30 minutes in every hour (Strategy 2a). For the RIVEC simulations the RIVEC controller took over the operation of the HRV unit, thus overriding the timer (Strategy 2b).

The quoted *Apparent Sensible Effectiveness* (ASE) for existing HRVs was used for the energy calculations to determine the temperature of air supplied to the space (T_{to_space}):

$$ASE = \frac{T_{out} - T_{to\_space}}{T_{out} - T_{from\_space}} \tag{15}$$

Central Fan Integrated Supply

The CFIS operated every minute that the forced air system operated (Strategies 3a and 3b). The outside air damper was sized so that the ventilation airflow rate supplied by the CFIS met the ASHRAE 62.2 whole-house minimum. Fan power requirements for the air handler remained unchanged from those used for standard HVAC operation.

Economizers

The economizers in this study operated when the outdoor temperature was 3.3°C (6°F) or more below the indoor set point and the house temperature was greater than 21°C (70°F) (Strategies 4a and 4b). The HVAC system air handler was used to draw in the outside air and then distribute it to the occupied zone via the heating/cooling ducts. For each house size and climate zone the economizer was sized to match the largest airflow rate and power consumption of the air handler unit. The air handler typically operated at the cooling airflow rate.

Because the economizer system acts as a large supply fan, a hole with area 'A_{relief}' opened in the building envelope to ensure the house was pressure balanced. This hole was sized to result in approximately 2 Pa of house pressurization based on the size of the economizer fan, which was dependent on the HVAC equipment sizing. The values of A_{relief} used for each house are as follows:

- A_{relief} ≈ 0.17 m^2 (1.83 ft^2) for Prototype B
- A_{relief} ≈ 0.31 m^2 (3.34 ft^2) for Prototype C
- A_{relief} ≈ 0.37 m^2 (3.98 ft^2) for Prototype D

Exogenous Ventilation

We included intermittent operation of bathroom, kitchen and clothes dryer fans, also sized to meet ASHRAE 62.2. Bathroom fans operated at 25 L/s (50 cfm). Kitchen range hood fans had airflow rates of 50 L/s (100 cfm). Clothes dryer fans were simulated as exhaust fans with an airflow rate of 75 L/s (150 cfm).

Building Occupancy and Fan Scheduling

The houses were assumed to be unoccupied between 8am and 4pm every weekday, and occupied for the rest of the time. During unoccupied hours, the RIVEC algorithm operated using the higher limit for relative exposure given in Equation 11. Recall that the dose and exposure calculations were continuous whether the home was occupied or not. However, the calculation of relative dose and exposure for comparison between different ventilation strategies (and comparison to ASHRAE 62.2) used only occupied hours.

Operation of additional ventilation systems was based around the above occupancy schedule. On weekdays one bathroom fan was operated for 30 minutes per occupant every morning (between 6.30am and 7.30am to simulate showering) and again for 10 minutes per occupant in the evening (between 4pm and 11pm). On weekends the fan run time per occupant was the same as for weekdays but the times were only constrained between 7am and 11pm. An algorithm was used to add some degree of daily variability into the bathroom fan schedules. This algorithm did not violate the criteria of a maximum of 40 minutes operation per occupant per day and the weekend/weekday occupancy time periods. The algorithm was used to generate a full yearlong schedule for each of the three home sizes. For each home, the same yearlong, pre-calculated schedule was used in each simulation. Thus, there was day-to-day variability in bathroom fan use as the simulations progressed through the year, but the same variability was used for each simulation. In other words, for any given day of the year for a given house the schedule was the same. The five different ventilation strategies (including the reference case) all used the same schedule to allow the energy results to be directly comparable.

The kitchen range hoods operated for one hour per day between 5.30 pm and 6.30 pm. On weekends there was an additional 30 minutes of operation in the morning between 9.30 am and 10.00 am.

The clothes dryer operated irrespective of occupancy. Two laundry days each week were simulated for the small and medium houses, and three laundry days for the large house. Dryer operation was for three consecutive hours between 11 am and 2 pm to avoid peak times (assuming an energy-conscious homeowner using a timer to operate the dryer).

3. RESULTS AND DISCUSSION

All the energy calculations refer to energy used for space conditioning and ventilation, and do not include lighting, appliances or other occupant related loads. For all the simulation results, the gas burned by the furnace has been converted into kilowatt-hours using a 29.3 kWh/therm conversion ratio so that it may be included in the total energy calculation together with the electrical energy consumed by the air conditioning, air handler and mechanical ventilation.

Strategy 0: Reference Case

Strategy 0 has no whole-house mechanical ventilation and will be used as a reference for the IAQ and energy calculations. Strategy 0 assumed that the heating, cooling and auxiliary ventilation systems (bathroom, kitchen and dryer fans) operated as usual. The resulting total building energy use for one year is shown in Table 10.

The other simulation results were compared to these reference case results to ascertain the additional building energy use caused by introducing a whole-house ventilation system, herein referred to as the 'ventilation energy'. The difference between the total building energy use with whole-house ventilation and the reference case will be the energy associated with ventilation for that particular strategy.

Table 10: Energy used by the reference case houses with no whole-house mechanical ventilation system

House	Leakage ACH_{50} [/h]	Total House Energy Use per Climate Zone [MWh] or [kWh] x 10^3												
		2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2.0	9.2	9.3	14.6	11.5	11.2	16.3	14.5	12.5	19.2	15.6	18.2	22.7	29.2
	4.8	9.8	9.7	15.8	12.3	12.1	18.0	16.0	13.9	21.8	17.6	20.8	25.7	33.7
	8.0	10.6	10.1	17.2	13.3	13.2	19.9	17.9	15.6	24.8	19.9	23.7	29.3	38.9
Prototype C	2.0	15.4	15.7	24.5	19.5	20.6	28.3	25.3	22.2	33.3	27.2	30.3	40.7	52.3
	4.8	16.3	16.3	26.3	20.7	22.1	30.8	27.5	24.7	37.4	30.1	34.0	45.3	59.3
	8.0	17.4	17.0	28.4	22.2	23.8	33.7	30.1	27.7	42.2	33.5	38.2	50.7	67.2
Prototype D	2.0	19.8	20.0	31.0	25.1	26.9	39.5	35.3	31.9	45.9	37.8	39.1	49.1	62.8
	4.8	21.0	20.9	33.3	26.8	28.8	42.8	38.3	35.0	51.0	41.5	44.0	54.7	71.4
	8.0	22.4	21.8	35.9	28.6	31.0	46.7	41.7	38.8	56.6	45.8	49.5	61.2	80.9

Occupied Relative Dose and Exposure (RIVEC)

The occupied relative dose and exposure were controlled for all simulations by the RIVEC controller algorithm. Table 11 shows the minimum, mean and maximum values for the average annual occupied relative dose and exposure for all climate zones, house sizes and envelope leakages. To obtain exact equivalence to ASHRAE 62.2 compliant continuous mechanical ventilation systems, a mean annual occupied relative dose of 1.00 is required. Values below 1.00 indicate a lower dose and exposure and better IAQ than a minimally compliant ASHRAE 62.2 ventilation system. Table 11 shows that the average annual occupied relative dose and exposure never exceed 1.00, indicating that the RIVEC controller is providing equivalent (or better) ventilation compared to ASHRAE Standard 62.2. When using the economizer, the mean annual dose and exposures are approximately 10% below unity due to the large size and airflow rate of the economizer fan.

Table 11: Average annual occupied relative dose and exposure for each mechanical ventilation strategy (all climate zones, house sizes and envelope leakages).

		1. WHOLE HOUSE FAN	2. HRV	3. CFIS	4. ECONOMIZER
Occupied Relative Exposure	Min	0.98	0.97	0.98	0.85
	Mean	0.99	0.97	0.99	0.90
	Max	1.00	0.98	1.00	0.95
Occupied Relative Dose	Min	0.99	0.98	0.99	0.88
	Mean	0.99	0.98	0.99	0.92
	Max	1.00	0.98	1.00	0.96

The values in Table 11 are calculated assuming a constant level of infiltration equal to the ASHRAE 62.2 default because RIVEC cannot know the true contribution of infiltration towards the whole-house air exchange rate. Infiltration still has to be accounted for to avoid oversizing whole-house ventilation fans. In order to calculate the 'real' relative dose and exposure, the actual airflow rate of the house, consisting of the true infiltration airflow rate (the airflow through the building envelope, not the assumed default, $Q_{infiltration}$) and the mechanical flows, was used. Figure 7 (a and b) through Figure 11 (a and b) summarize an example of the one-hour annual average, and one-hour minimum and maximum peak occupied relative exposure and dose levels for Prototype C homes with an envelope leakage of 4.8 ACH_{50} for each climate zone. All of the one-hour maximum exposure values are below 3.0, meaning that the one-hour maximum acute-to-chronic ratio of 4.7 and the 8-hour maximum of 5.4 outlined in Table 1 are not exceeded. The relative dose maximums do not exceed 1.5 so the 24-hour maximum acute-to-chronic ratio of 2.5 is also not exceeded. The results for the other houses and envelope leakages are presented in Appendix C.

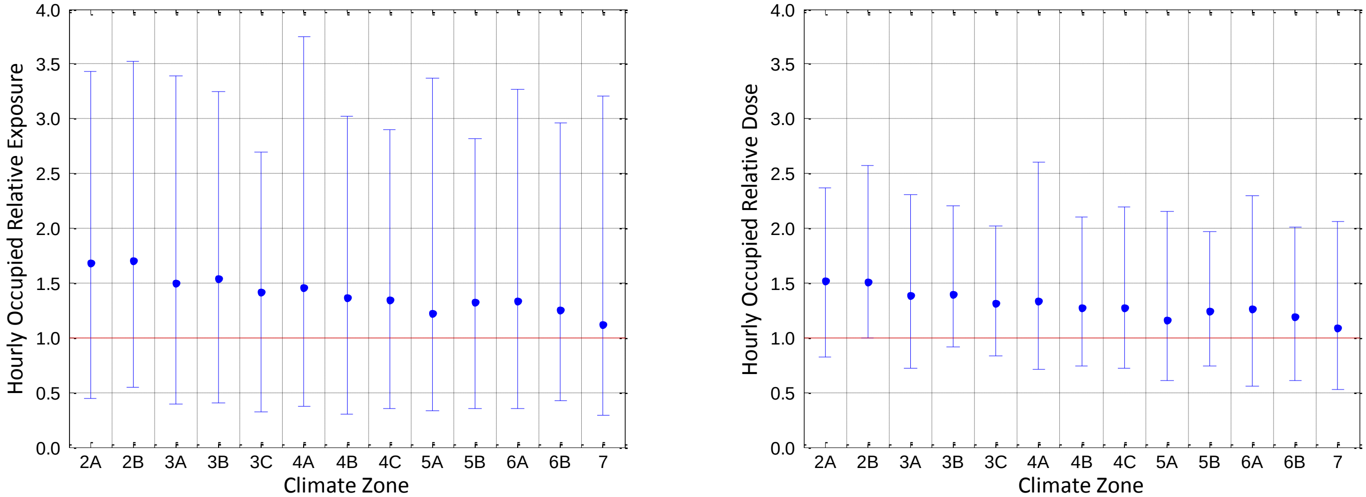


Figure 7a and b: Strategy 0 (Reference). Prototype C house with envelope leakage 4.8 ACH_{50}.

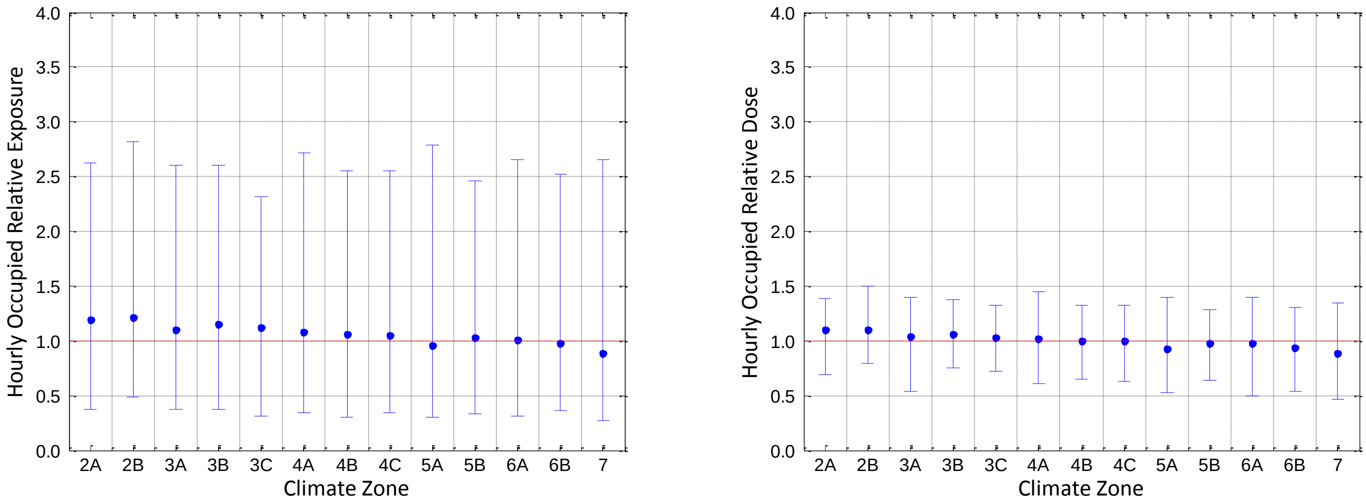


Figure 8a and b: Strategy 1 (Whole-House Exhaust). Prototype C house with envelope leakage 4.8 ACH_{50}.

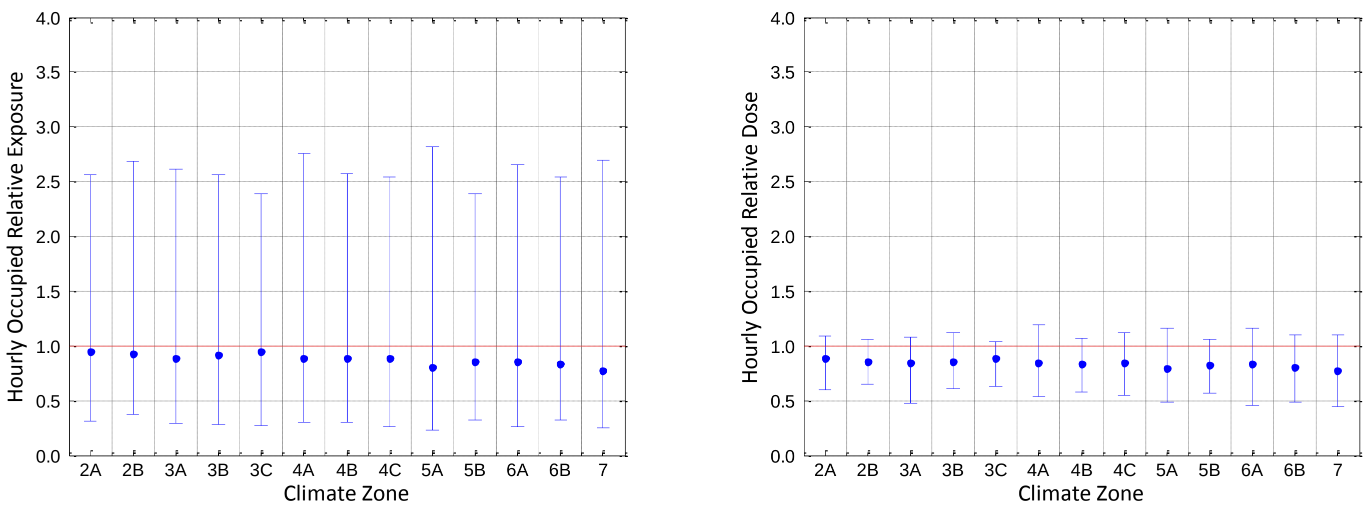


Figure 9a and b: Strategy 2 (HRV) . Prototype C house with envelope leakage 4.8 ACH_{50}.

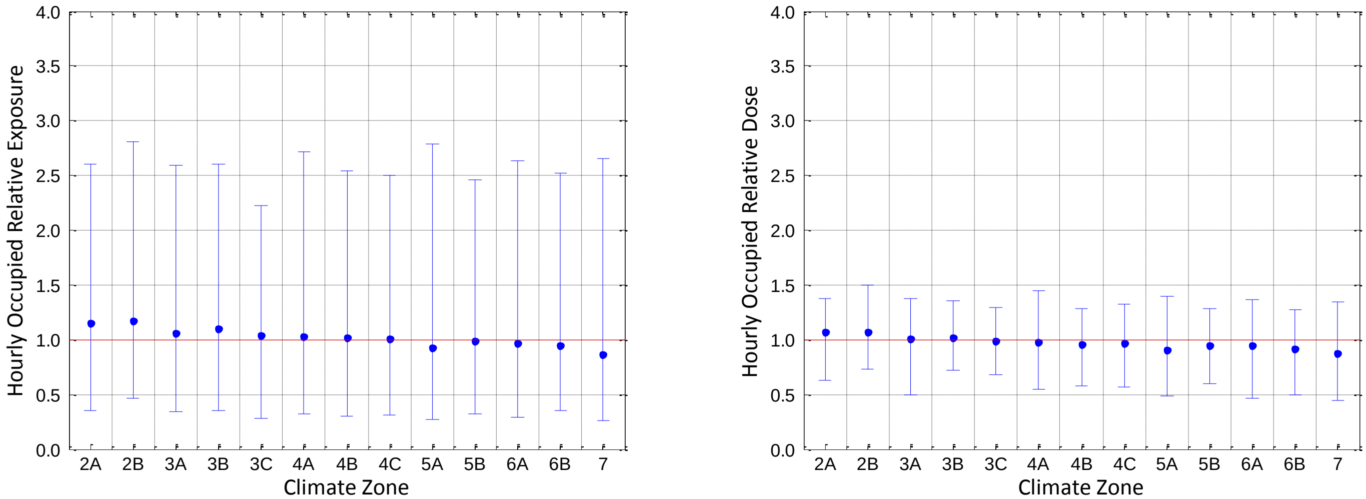


Figure 10a and b: Strategy 3 (CFIS + Whole-House Exhaust) . Prototype C house with envelope leakage 4.8 ACH_{50}.

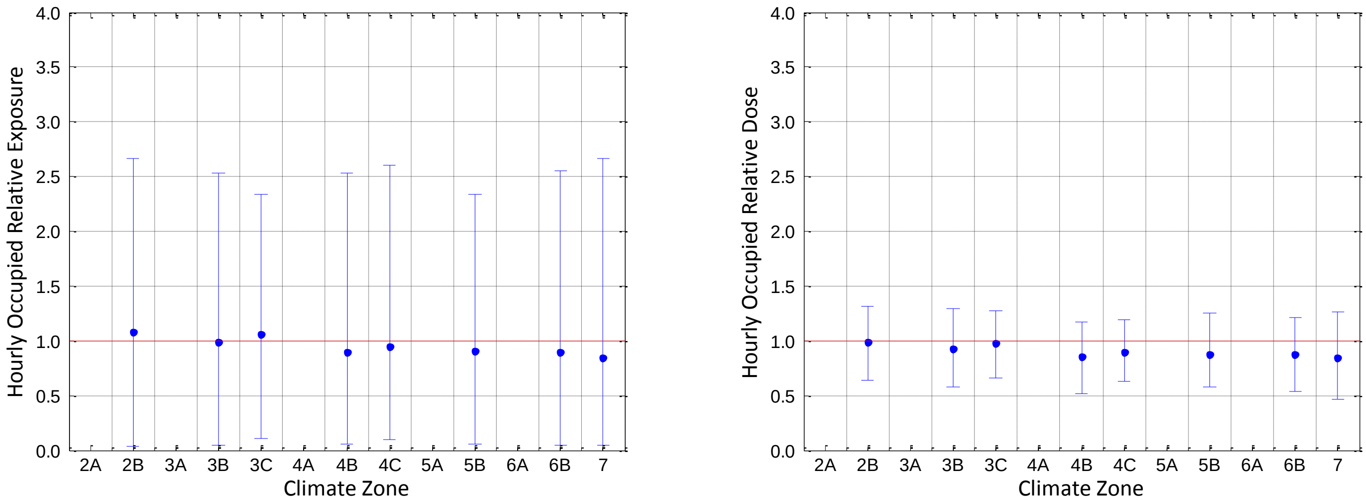


Figure 11a and b: Strategy 4 (Economizer + Whole-House Exhaust) . Prototype C house with envelope leakage 4.8 ACH_{50}.

RIVEC Fan Run Times

Ventilation strategies 1, 3 and 4 (whole-house exhaust fan, CFIS and economizer) all used an ASHRAE Standard 62.2 compliant whole-house fan. This fan was operating either continuously or under RIVEC control. The results of the calculated RIVEC fan run time, expressed as the fraction of time in the year that fan was operating, are shown in Table 12. In the non-RIVEC case, the HRV operated for only 50% of the year (30 minutes every hour); therefore, Table 12 shows the runtimes of the HRV as both a percentage of the whole year and of half the year (in parentheses).

Table 12: RIVEC-controlled exhaust fan and HRV runtimes as a percentage of the total year. The percentages in parentheses for the HRV unit are the runtimes of half the year

RIVEC Fan Run Times [% of year]				
	1. WHOLE-HOUSE EXHAUST	2. HRV	3. CFIS + WHOLE-HOUSE EXHAUST	4. ECONOMIZER + WHOLE-HOUSE EXHAUST
Min	43%	27% (54%)	43%	34%
Mean	47%	30% (60%)	47%	41%
Max	51%	31% (61%)	51%	48%

The RIVEC controller operates the whole-house ventilation fan or HRV between 34% and 61% of the year, depending on ventilation strategy, climate zone etc. This is a significant reduction from the continuously operating ASHRAE 62.2 compliant systems and will have consequential energy savings from reduced fan power and space conditioning.

Ventilation Energy Saved by Using RIVEC

The ventilation energy is all of the energy associated with adding whole-house ventilation to a house with no whole-house ventilation. This includes electrical fan energy plus the extra space conditioning energy that results from the increased airflow rate in the home. It is calculated by taking the difference in total annual energy between the house with a whole-house ventilation system and the same house with no whole-house ventilation system (Strategy 0) for a given climate zone. The results listed in

Table 13 to Table 16 show that, for all cases, RIVEC saves energy by reducing the ventilation rate of the home while maintaining IAQ equivalent to or better than ASHRAE 62.2. The amount of ventilation energy saved is dependent on ventilation strategy, house size and climate zone. Most of the space conditioning is heating, so the colder climates see the larger absolute energy savings. Nearly all peak period ventilation loads were removed. Due to the large number of simulations, the results are displayed in tabular form. More detailed graphs of the energy use are shown in Appendix A.

Strategy1: Whole-House Exhaust

In the simulations, the use of RIVEC to control a whole-house exhaust fan saved between 31% and 52% of the annual ventilation energy. The mean ventilation energy saved was 42%. This translates to a mean annual energy saving of 915 kWh.

Strategy 2: HRV

HRV ventilation shows lower percentile energy savings (because of the heat recovery), but higher absolute energy savings (because of the large fan power). The energy savings range from 14% to 39% with a mean of 34% or 840 kWh. In the hotter climate zones such as 2A and 2B (Houston and Phoenix) the HRV uses more energy relative to the whole-house exhaust due to small indoor-outdoor temperature differences (and therefore limited potential for heat recovery) and significantly higher additional fan energy from operating the central air handler (typically a factor of 10 higher than the exhaust fan in Strategy 1). The results show that this strategy is much more suitable in colder climate zones such as 5, 6 and 7 (Cool, Cold and Very Cold).

Strategy 3: CFIS with Whole-House Exhaust

CFIS ventilation simulations predicted energy savings between 25% and 47% with a mean of 36% or 857 kWh. The additional ventilation energy use is comparable to the whole-house exhaust system and is fairly independent of climate zone.

Strategy 4: Economizer with Whole-House Exhaust

Economizer ventilation simulations predicted energy savings between 36% and 1211%. For some of the houses in the warm climate zones (i.e. 2B, 3B and in some cases, 3C), the cooling contribution from the economizer reduces the total house energy use below that of the reference case with no whole-house mechanical ventilation. This results in energy savings on the order of 1000% for some cases. However, in absolute terms the energy savings are small, e.g. 573 kWh or 4.3% of the space conditioning energy for the year for the small, leaky house in climate zone 3B. Average ventilation energy savings in the warmer climate zones of 2 and 3 are 271% or 324 kWh. In the rest of the climate zones it is 48% or 621 kWh.

Table 13: Ventilation energy saved by using RIVEC for Strategy 1 (Whole-House Exhaust)

House	Leakage ACH_{50} [/h]	1. Whole-House Exhaust. Ventilation Energy Saved [%]												
		2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2.0	47	51	48	50	45	47	49	47	46	47	46	46	47
	4.8	48	52	48	50	47	47	49	49	47	49	48	49	47
	8.0	51	52	49	51	47	47	48	47	48	49	48	48	47
Prototype C	2.0	35	38	35	37	31	36	37	33	35	37	36	38	36
	4.8	37	41	38	39	35	36	38	36	36	37	37	38	36
	8.0	38	41	37	39	35	36	39	36	36	37	37	37	37
Prototype D	2.0	42	44	43	45	40	42	45	42	42	43	43	43	41
	4.8	42	46	43	45	41	42	44	42	41	42	42	43	41
	8.0	44	44	42	45	40	42	44	40	42	42	42	42	41

Table 14: Ventilation energy saved by using RIVEC for Strategy 2 (HRV)

House	Leakage ACH_{50} [/h]	2. HRV. Ventilation Energy Saved [%]												
		2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2.0	34	31	32	33	34	35	35	35	33	35	34	34	32
	4.8	33	31	32	32	35	34	34	34	33	34	33	33	32
	8.0	34	33	32	33	35	34	35	34	33	34	34	34	33
Prototype C	2.0	34	30	33	33	34	33	34	35	32	33	34	30	20
	4.8	34	29	31	33	35	34	34	35	32	33	34	27	17
	8.0	35	29	32	33	35	34	34	33	32	33	34	24	14
Prototype D	2.0	37	35	35	37	35	37	38	37	37	39	38	36	34
	4.8	38	35	35	37	35	38	37	37	38	37	38	36	34
	8.0	38	34	35	37	36	37	38	36	38	38	37	35	34

Table 15: Ventilation energy saved by using RIVEC for Strategy 3 (CFIS + Whole-House Exhaust)

House	Leakage ACH_{50} [/h]	3. CFIS. Ventilation Energy Saved [%]												
		2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2.0	39	42	40	43	40	38	40	41	40	40	42	47	46
	4.8	42	44	45	45	42	38	40	42	41	44	44	46	43
	8.0	43	44	44	45	41	37	38	40	39	42	43	44	40
Prototype C	2.0	28	33	30	30	25	28	29	28	31	34	31	42	39
	4.8	30	34	32	32	29	28	30	30	31	33	31	37	33
	8.0	30	34	31	32	29	28	30	30	30	32	30	35	32
Prototype D	2.0	35	37	35	38	33	35	36	36	34	36	38	39	36
	4.8	35	39	34	38	35	34	36	36	33	35	36	37	35
	8.0	37	35	33	37	34	33	35	34	32	35	35	36	33

Table 16: Ventilation energy saved by using RIVEC for Strategy 4 (Economizer + Whole-House Exhaust)

House	Leakage ACH_{50} [/h]	4. Economizer. Ventilation Energy Saved [%]												
		2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Pro B	2.0	-	152	-	207	97	-	61	55	-	51	-	51	48
	4.8	-	257	-	541	128	-	69	56	-	52	-	52	48
	8.0	-	686	-	1211	230	-	76	61	-	55	-	52	49
Pro C	2.0	-	124	-	117	92	-	44	38	-	39	-	38	36
	4.8	-	223	-	181	178	-	54	43	-	38	-	37	36
	8.0	-	350	-	919	405	-	54	44	-	39	-	39	37
Pro D	2.0	-	121	-	96	84	-	54	46	-	45	-	43	41
	4.8	-	151	-	109	113	-	56	50	-	47	-	42	41
	8.0	-	220	-	162	174	-	54	52	-	47	-	42	41

Strategies 1 to 4

On average across all climate zones, house sizes and envelope leakages the RIVEC controller saved ventilation energy of 42% for Strategy 1 (whole-house), 34% for Strategy 2 (HRV), 36% for Strategy 3 (CFIS) and 271% in the hot climates or 48% in the colder climates for Strategy 4 (Economizer – minus the humid climate zones). The fractional energy changes were consistent across climates with just a few percentage point differences (typically 5 to 10% excluding the economizer simulations). This is an average of 37% for the first three mechanical ventilation strategies, again excluding the economizer, which distorts the mean. The maximum absolute energy saved from RIVEC for ventilation strategies 1, 2, 3 and 4 is 2,194, 1,673, 2,096 and 2,210 kWh respectively.

Leakage & House Size Dependency for RIVEC-Controlled Systems

The simulated results for ventilation strategies 1 to 4 show little dependency on house envelope leakage on the amount of ventilation energy saved by using RIVEC. For Strategy 1 (whole-house exhaust), the mean difference between energy saved by RIVEC for the three envelope leakages is 0.6% with a maximum difference of 2.2%. For the Strategy 2 (HRV) simulations, the mean difference between energy saved by RIVEC for the three envelope leakages is 0.3% with a maximum difference of 6.3%. Strategy 3 (CFIS) has a mean saving of 0.3% and maximum of 6.8%. The results from strategy 4 (economizer) are more complex due to the simulations where the economizer cooling contribution reduces the total house energy use below that of the reference case. Disregarding those cases, the mean difference between energy saved by RIVEC for the three envelope leakages is 2.3% with a maximum difference of 14.8%. These simulation results show that RIVEC energy savings are robust over a wide range of envelope leakage.

There is no general trend of house size on ventilation energy savings; RIVEC saved more in the small and large houses than in the medium sized house. Some of this variability is because the geometry of the three buildings does not scale with floor area. Prototype B and C are both single-story buildings while prototype D is a two story building with a different shape. The garage size for prototypes B and C was the same, thus the ratio of the different wall lengths was not the same for both houses. This will affect the scaling of the wind pressures on the walls. In addition, the difference in occupant density results in target airflow rates that did not scale linearly. Regardless of these differences, the simulation results show that the RIVEC savings are robust over a range of house sizes.

Economizer Operation Times

Figure 12 shows the times of the year during which the economizer operates. The results are presented for the Prototype C house with medium envelope leakage (4.8 ACH_{50}). The mild, dry climate zones (e.g. 4B: 735 hours, 5B: 602 hours) have the most hours of operation, especially during the summer months when indoor temperatures are high enough for the economizer to operate. In the hotter climates (e.g. 2B and 3B) the outdoor air temperature at night is too high for economizer operation during the summertime and it only operates during the shoulder seasons. The coldest climate (7) has the least amount of economizer operation due to low outdoor temperatures.

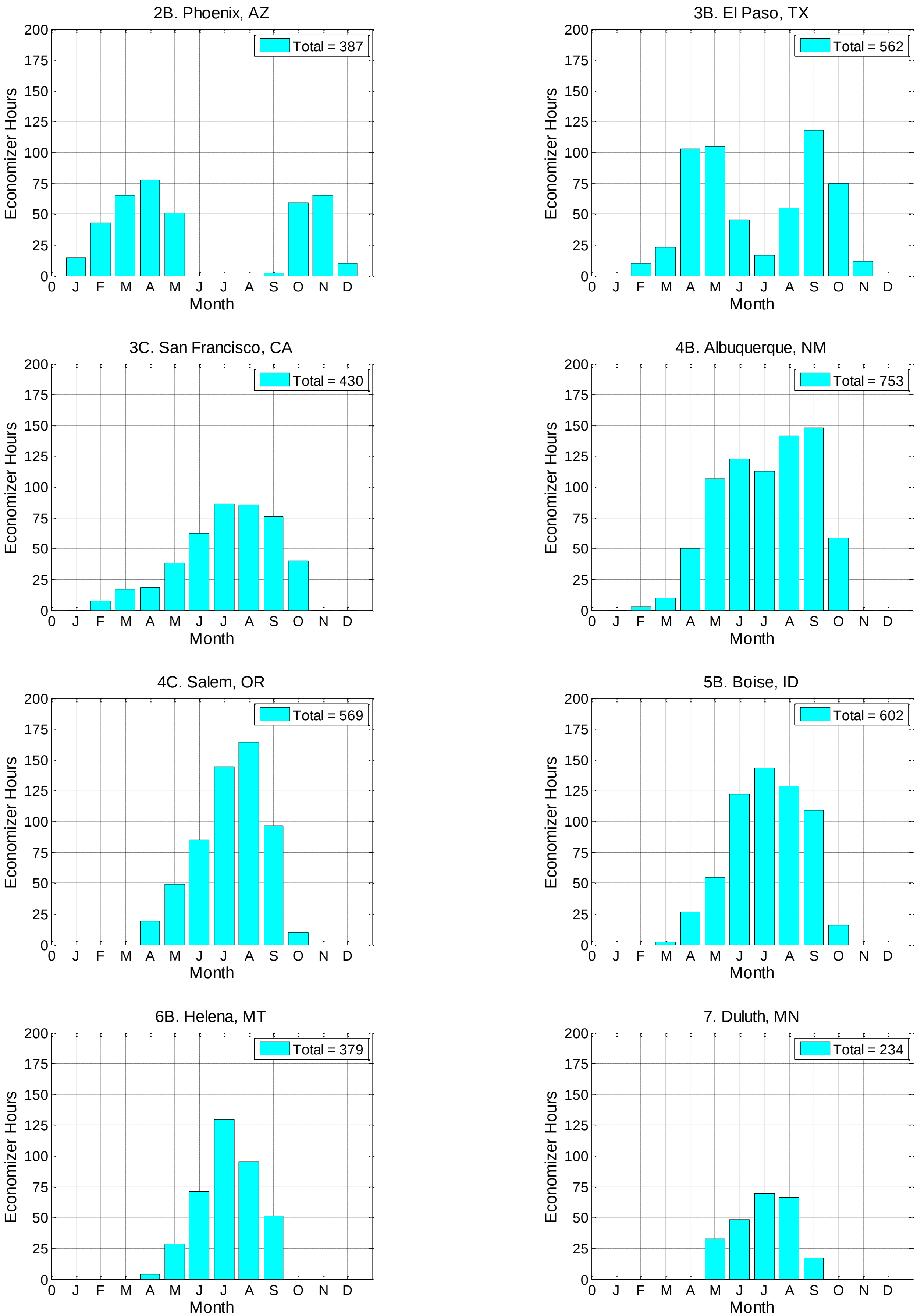


Figure 12: Hours of operation for the economizer by month (Prototype C house with medium envelope leakage)

Peak Load Reduction

RIVEC acts as a demand response system by turning off the whole-house ventilation during peak load periods. Reducing the outside ventilation air entering the house during the hottest and coldest parts of the day should reduce the demand on the heating and cooling equipment. Two types of load reduction are discussed in this report. The *critical* peak load reduction and the *average* peak load reduction.

Critical Peak Load Reduction

The *critical peak* represents the period in the year when the demand on the space conditioning equipment is the largest. The heating critical peak is defined here as the average total building power draw for the five hours with the largest heating load. The cooling critical peak is the same except for the largest cooling load. The total power used by the air handler, furnace, air conditioner and ventilation system was calculated for each hour of the year. The hourly data was sorted to find the hours of maximum heating and cooling power draw for the non-RIVEC case that occurred during the peak times programmed into RIVEC (i.e. 2 a.m. to 6 a.m. for heating and 4 p.m. to 8 p.m. for cooling). The power draw for the corresponding hours from the RIVEC simulations was compared to the power draw for the peak hours in the non-RIVEC case. The results were averaged over the highest five power draw hours for the year to remove some of the sensitivity to selecting an individual peak hour.

Strategy 1 was chosen for this analysis because a continuous exhaust is likely to be the most common whole-house ventilation system, and because the continuous exhaust gives results that are conservative in terms of energy savings. The critical peak period power reductions in electricity and gas consumption are summarized in Figure 13 through Figure 15 for the medium sized, Prototype C house with medium air leakage. Gas consumption of the furnace is included in Watts for better comparison and so that it can be combined with the air handler and ventilation fan power. Furnace and compressor run times over the five critical peak hours are included in the figures. The results for all homes and air leakage values are presented Appendix B.

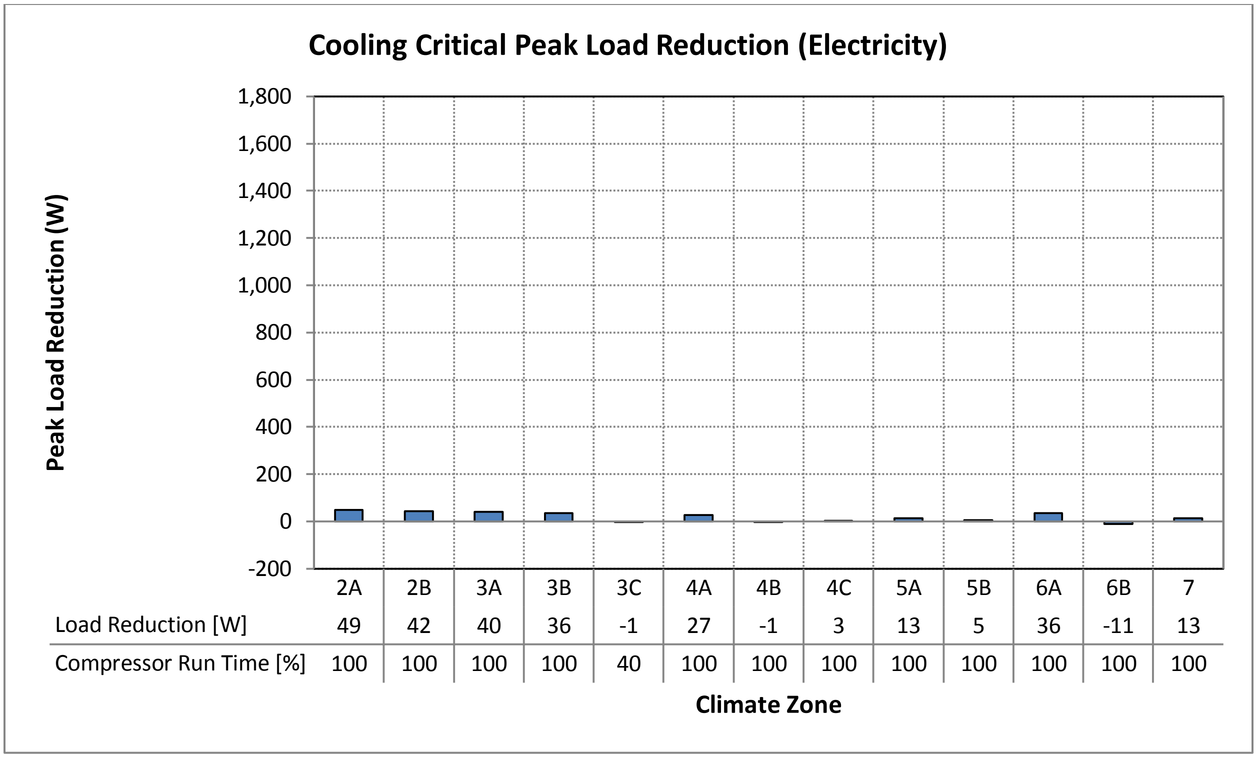


Figure 13: Cooling critical peak load avoided using RIVEC (whole-house exhaust, Pro C house with medium envelope leakage)

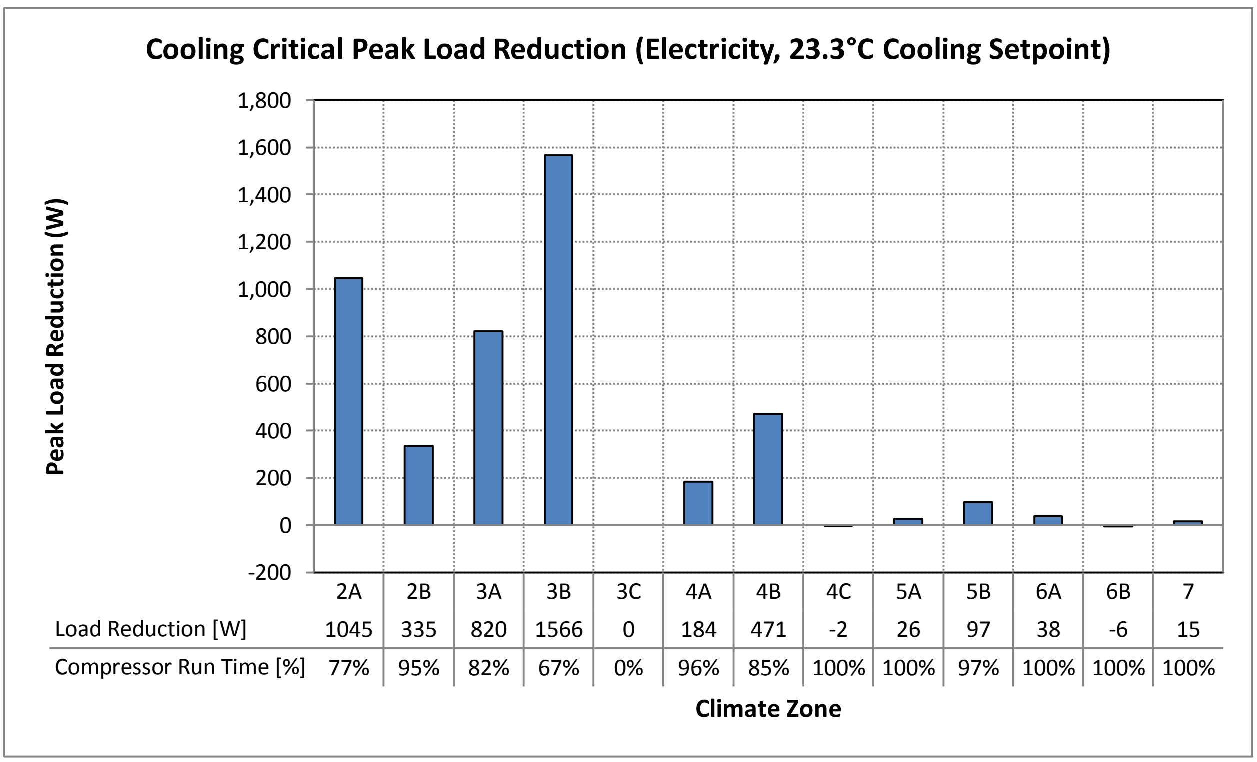
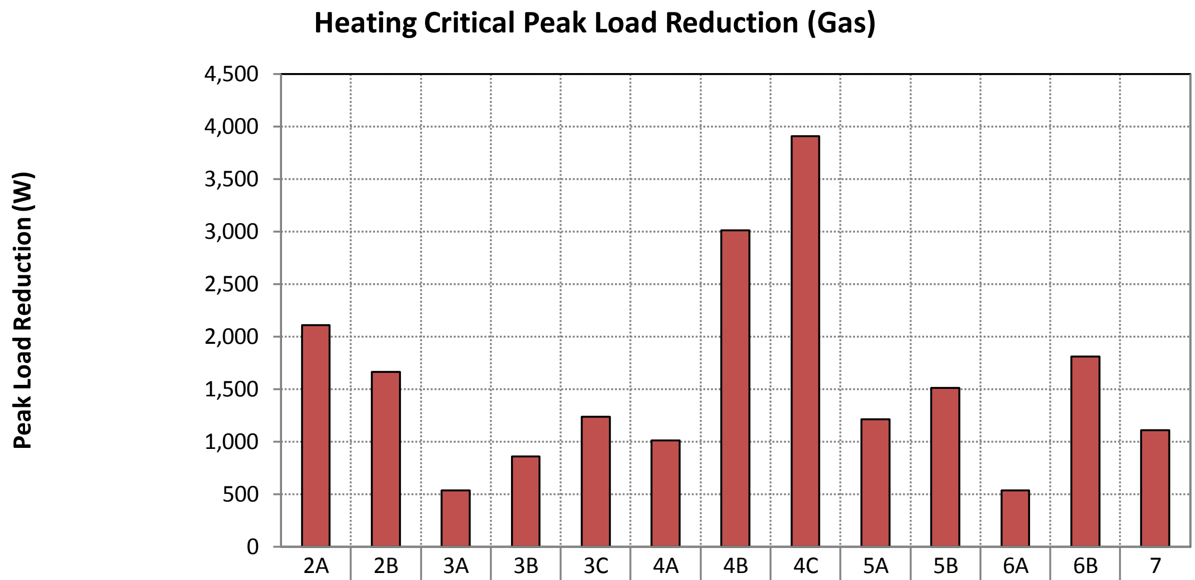


Figure 14: Cooling critical peak load avoided using RIVEC with a 23.3°C cooling set point throughout the cooling season (whole-house exhaust, Pro C house with medium envelope leakage)



	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Load Reduction [W]	2110	1660	536	861	1234	1011	3009	3908	1210	1510	536	1810	1110
Compressor Run Time [%]	86	74	86	94	89	93	80	74	87	70	98	71	83

Climate Zone

Figure 15: Heating critical peak load avoided using RIVEC (whole-house exhaust, Pro C house with medium envelope leakage)

The results in Figure 13 show the cooling critical load reductions from using RIVEC with the thermostat temperature set points in

Table 7. Savings are small because the set points already factor in peak load avoidance by raising the cooling set point during the day. This helps prevent the air-conditioner from running. Figure 14 shows the cooling critical peak reduction when the cooling set point has been held constant at 23.3°C (74°F) for the entire cooling season, which results in much larger load reductions. The maximum reduction is 1,566 W in the warm, dry climate zone 3B (El Paso, TX).

Sizing of the cooling equipment is an issue. For RIVEC to reduce critical peak loads, the equipment needs to be sized so that it may cycle. If it cannot cycle, then the compressor simply runs all of the time during the critical peak hours whether or not the ventilation rate is reduced. An example of this is the hot, dry climate zone 2B (Phoenix, AZ) with hot summer days. The air conditioning compressor runs for 95% of the time over the five critical hours; thus critical load reductions are smaller than those calculated for the other hot climate zones where the compressor runs for a small fraction of the critical peak period.

Figure 15 shows gas reductions during the heating critical peak period. These heating reductions are much larger than the cooling reductions, but less significant because reducing electricity peaks is more important from the perspective of utility capacity. For utilities where electric heat is common, this winter peak is of greater interest. The largest reduction is 3,908 W in climate zone 4C (Salem, OR). Again, equipment sizing is something of an issue, with (generally, but not always) smaller peak reductions possible in the climate zones where the furnace cycles less.

Average Peak Load Reduction

The difference in load between coincident peak heating or peak cooling periods between the non-RIVEC and RIVEC results were summed and then averaged for the whole year. Figure 16 through Figure 18 show the annual average peak load reduction for electricity and gas. Again, results are for ventilation Strategy 1 (whole-house exhaust) using the Prototype C home with medium air leakage.

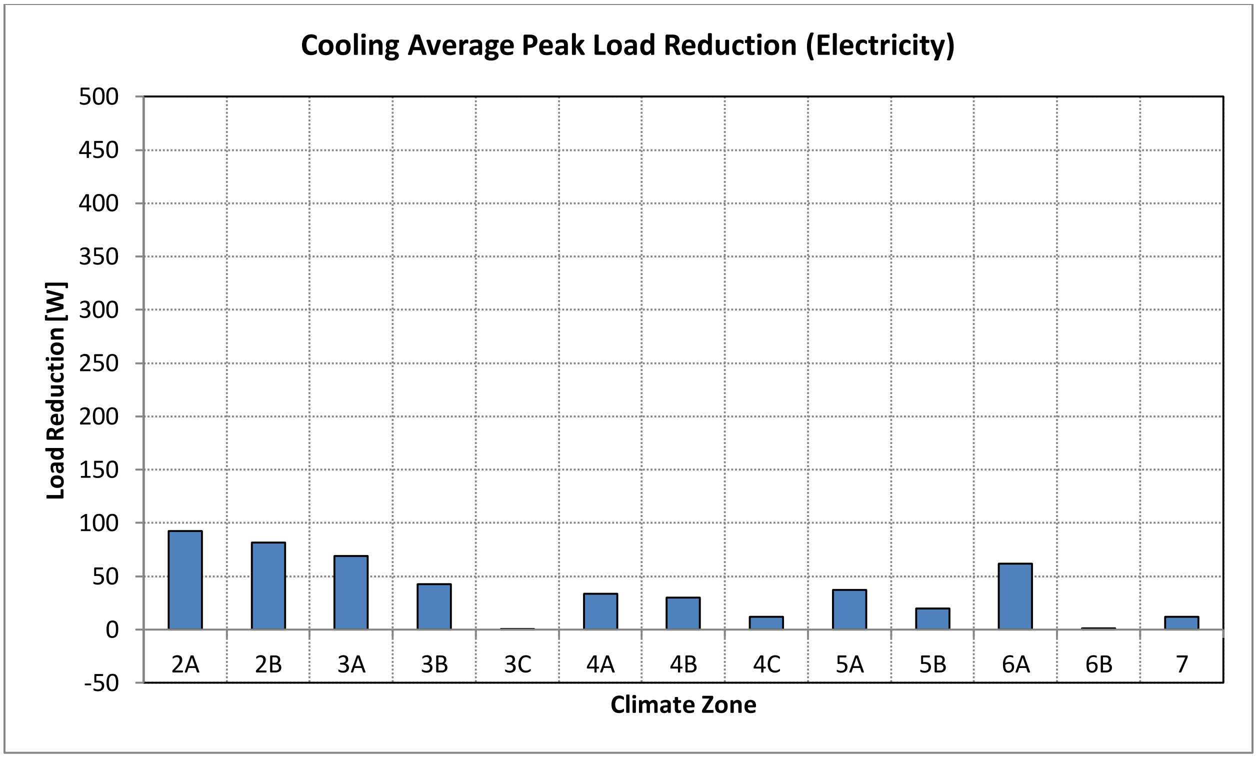


Figure 16: Cooling average peak load reduction over the year from using RIVEC (whole-house exhaust, Prototype C, medium leakage)

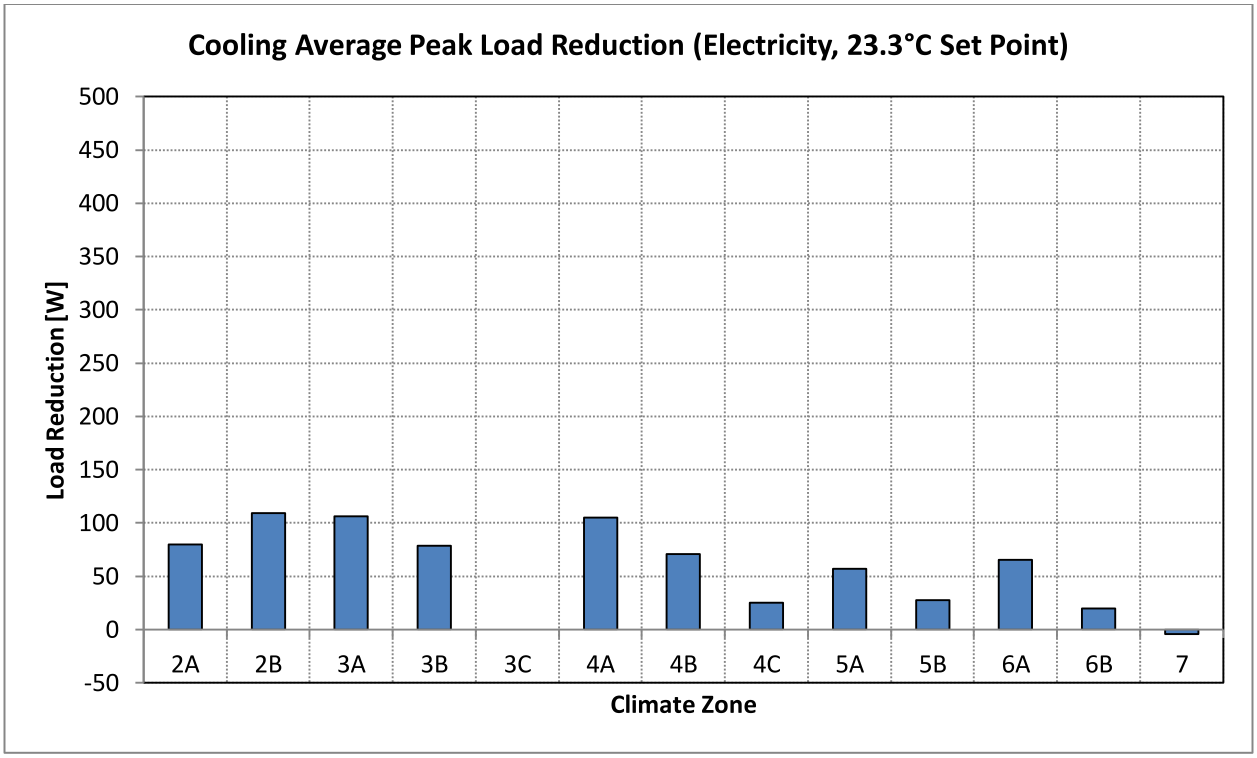


Figure 17: Cooling average peak load reduction over the year using RIVEC with a cooling set point of 74°F (whole-house exhaust, Prototype C, medium leakage).

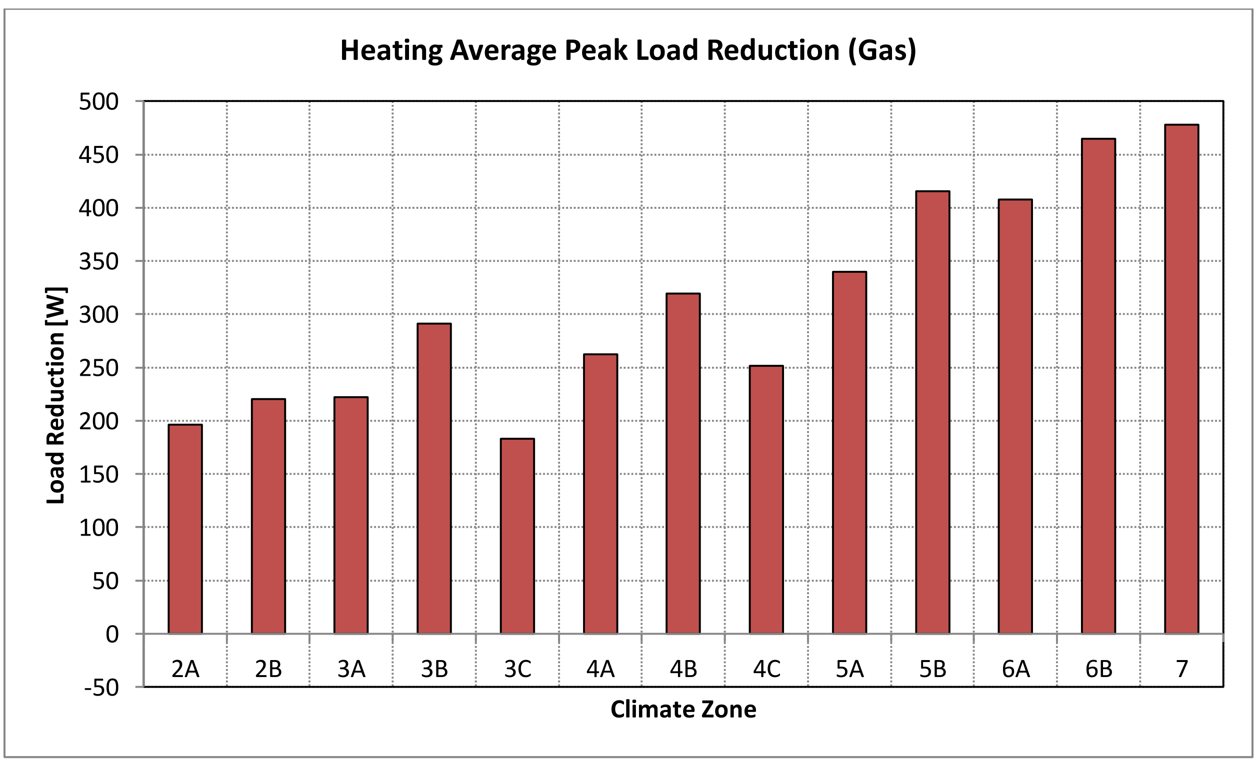


Figure 18: Heating average peak load reduction over the year from using RIVEC (whole-house exhaust, Prototype C, medium leakage)

Figure 16 shows the annual average cooling peak reduction with the temperature set points listed in

Table 7. The average peak load reduction is highest for the hottest climate zones, but never more than 100 W. Figure 17 shows the annual average cooling peak reduction with the constant 23.3°C set point. As expected, the reductions are slightly larger because there is almost no mechanical cooling in climate zone 3C (San Francisco), so only very small peak savings are available.

Figure 18 shows that annual average heating load reductions are possible in all 13 climate zones. The highest power reduction (478 W) is in the coldest climate zone 7 of Duluth, MN. The lowest (183 W) is in climate zone 3C. On average, across all climate zones RIVEC removes 312 W from the heating peak period over the year.

4. CONCLUSIONS

Simulations showed that the RIVEC advanced ventilation controller will:

- typically save at least 40% of ventilation related energy use while maintaining equivalence to ASHRAE Standard 62.2
- not introduce any problems with acute exposures
- provide ventilation energy savings that are robust regardless of climate, house size and envelope leakage
- provide absolute energy savings of 500 to 2,000 kWh/year depending on climate – with more temperate climates at the lower end of energy savings estimates
- reduce peak power consumption up to 2 kW for a typical home.

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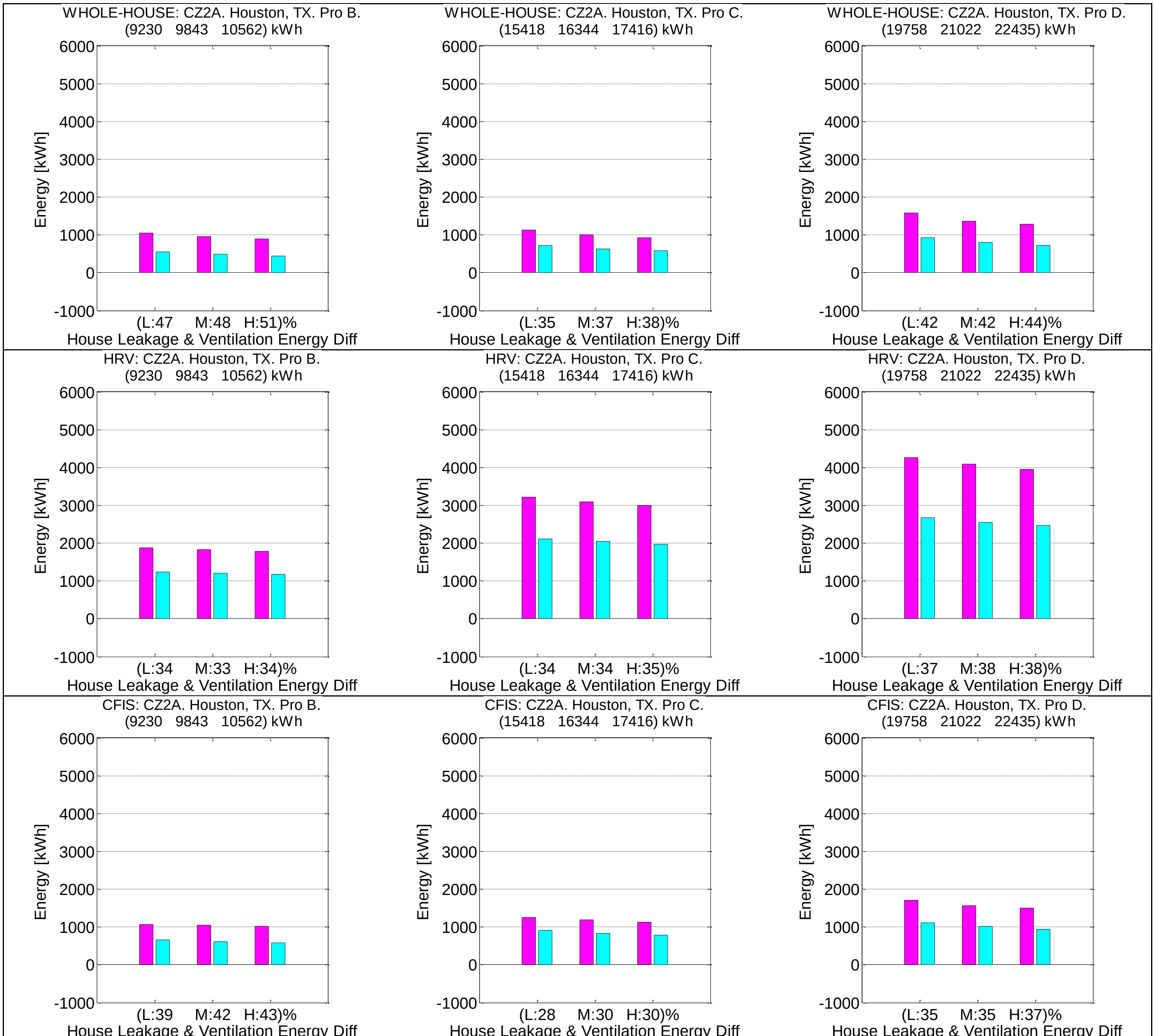
Appendix A: Ventilation Energy Saved by Using RIVEC for Whole-House Mechanical Ventilation Systems

Figure 19 to Figure 31**Error! Reference source not found.** show the additional energy consumed for ventilations strategies 1 through 4 adding a whole-house mechanical ventilation system with (pink) and without (light blue) RIVEC. The results are arranged by climate zone. Each individual graph shows the additional energy used for a single house size and the three different envelope leakages:

- Low (L) 2.0 ACH_{50}
- Medium (M) 4.8 ACH_{50}
- High (H) 8.0 ACH_{50}

The energy [kWh] used by the reference case houses with no whole-house mechanical ventilation is contained in parentheses in order of envelope leakage level underneath each individual figure title. The percentage of total ventilation energy saved is in parentheses above the x-axis label.



N/A N/A N/A

Figure 19: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 2A Houston, TX

Non-RIVEC RIVEC

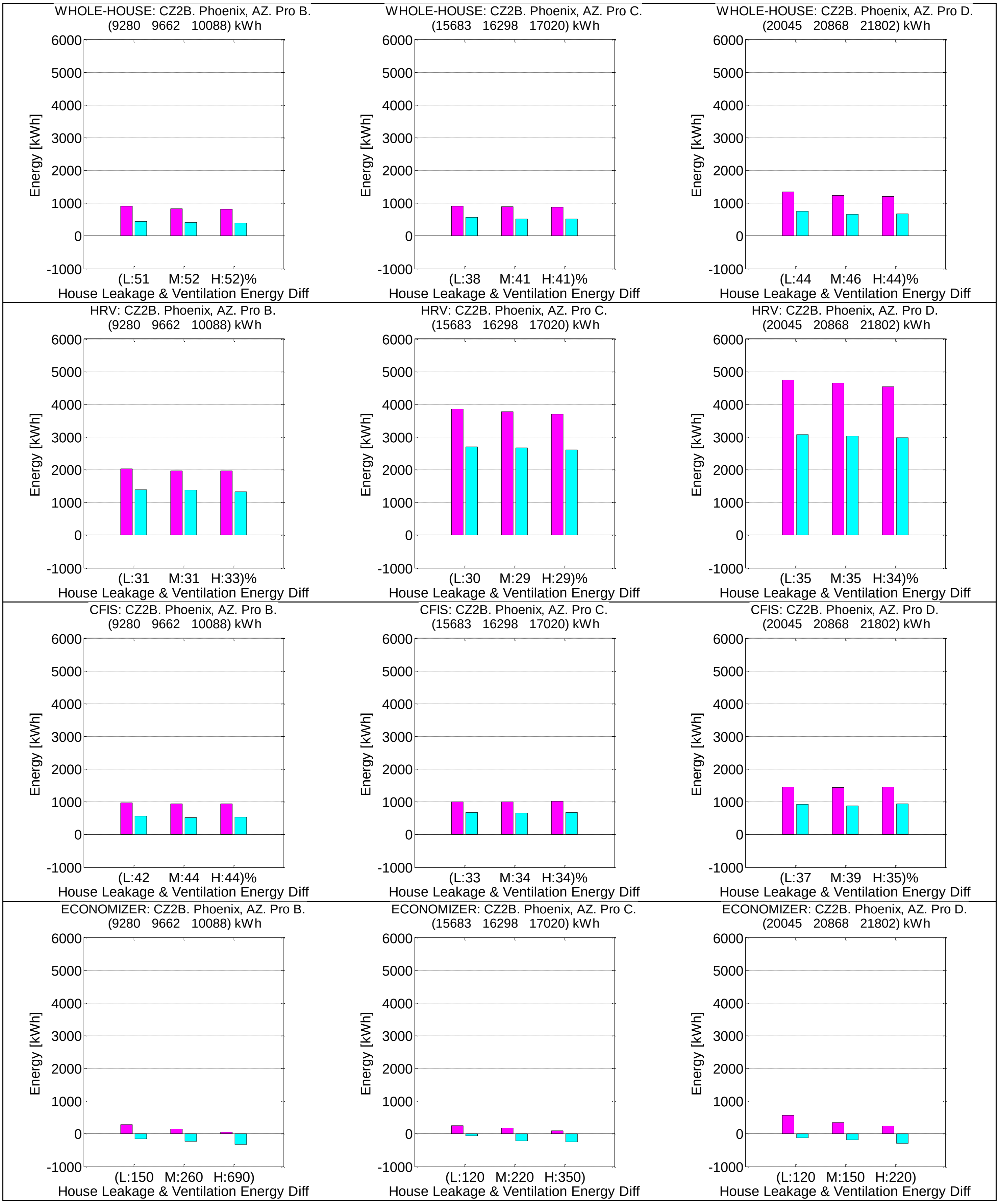


Figure 20: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 2B Phoenix, AZ

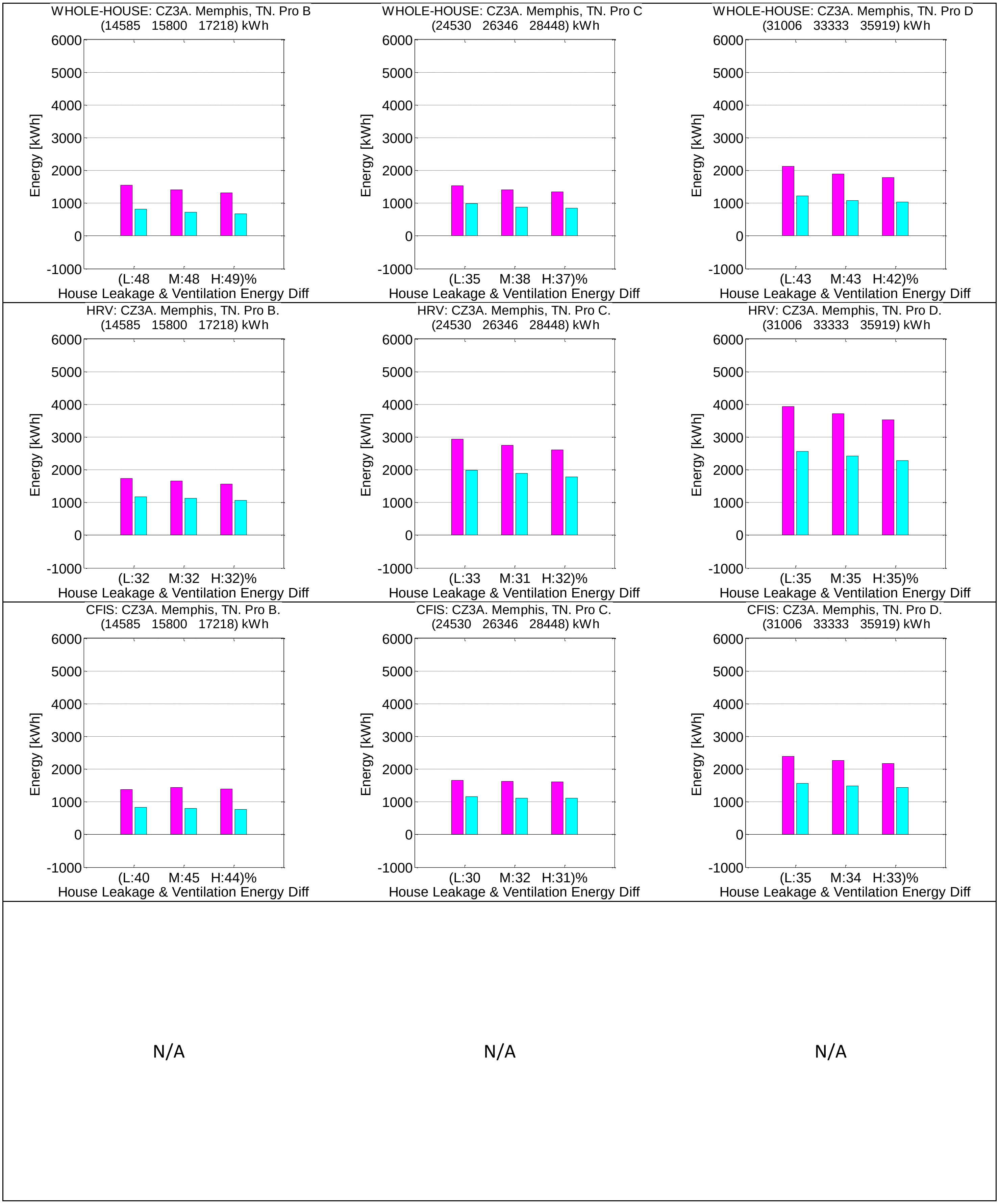


Figure 21: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 3A Memphis, TN

Non-RIVEC RIVEC

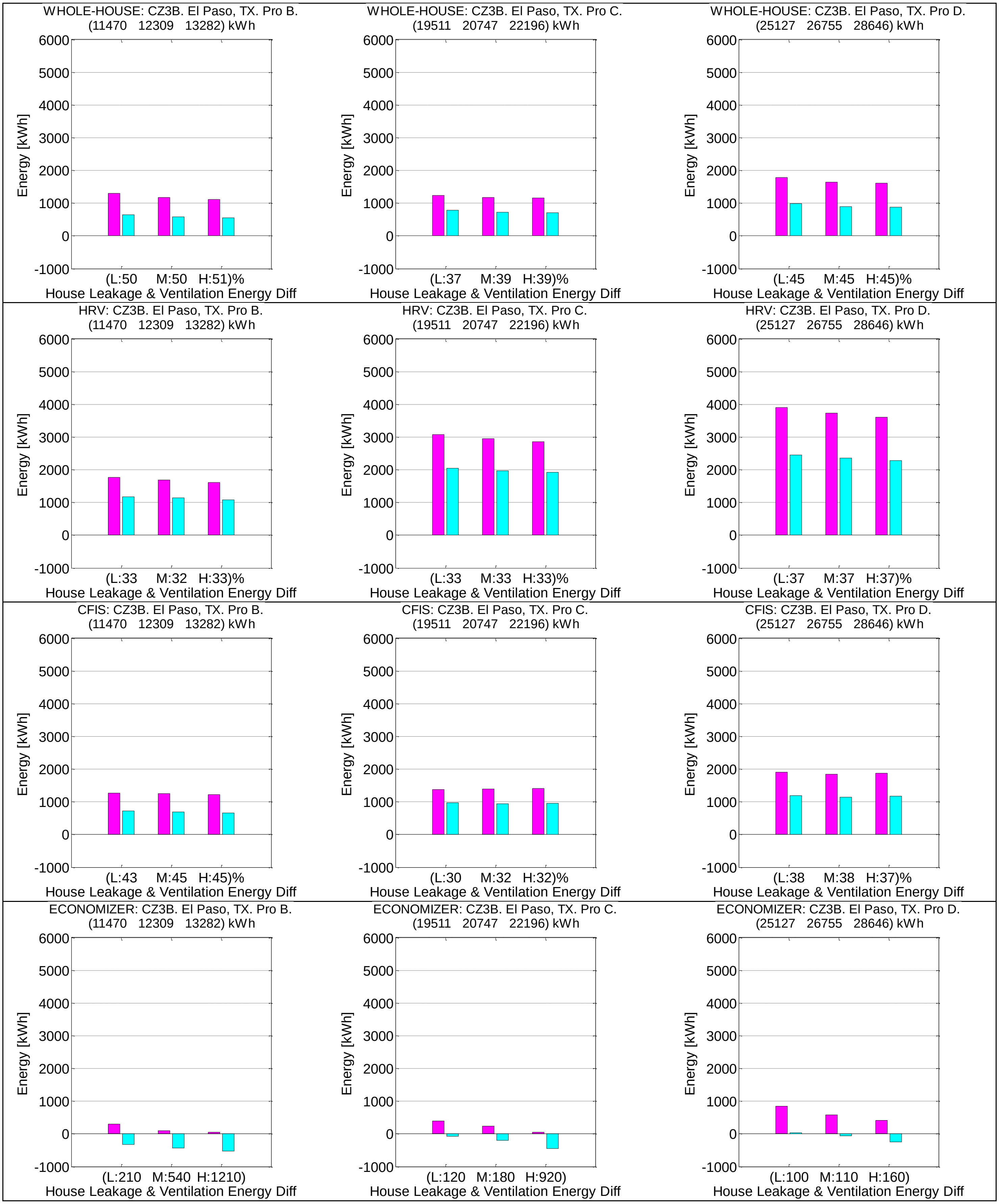


Figure 22: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 3B El Paso, TX

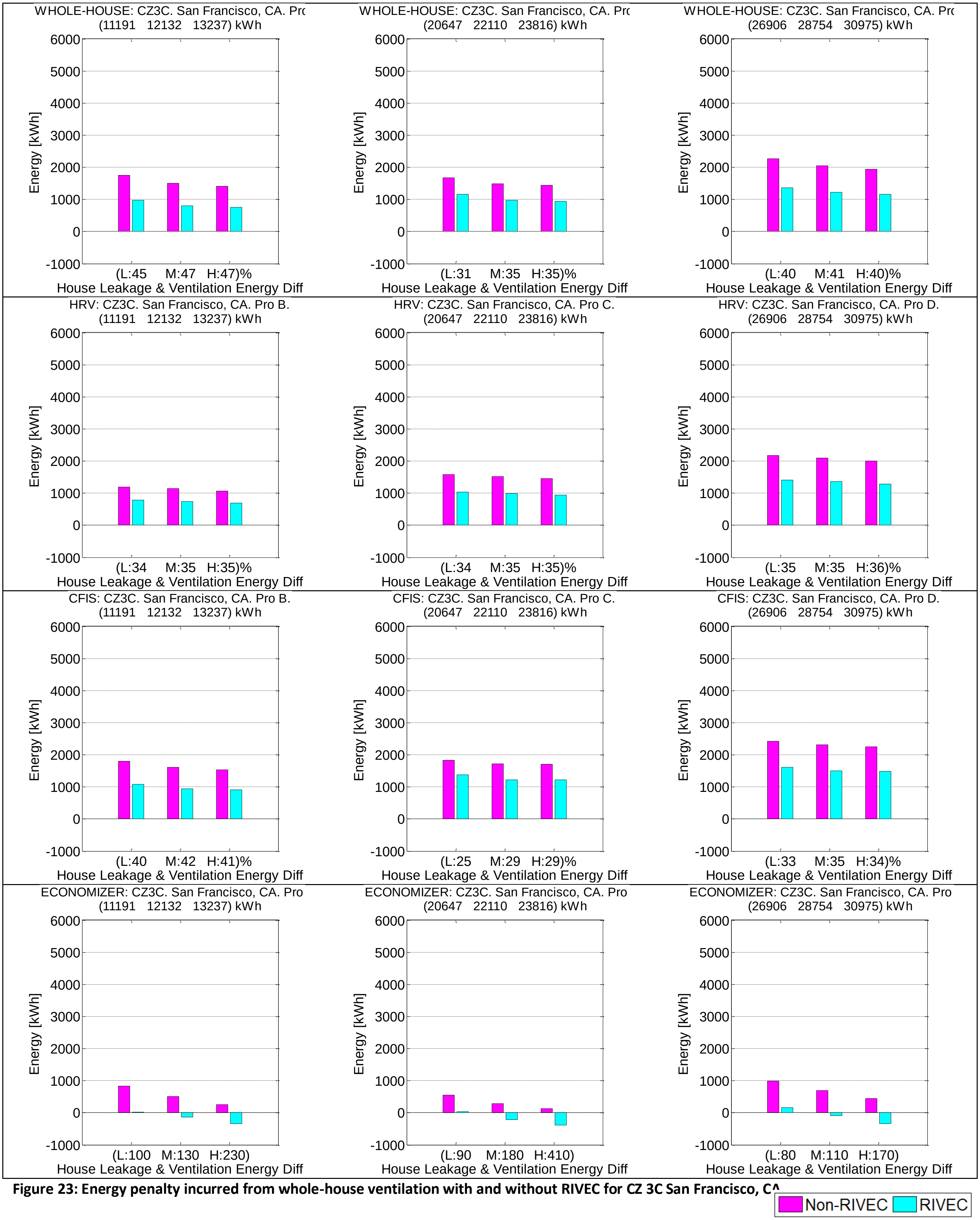
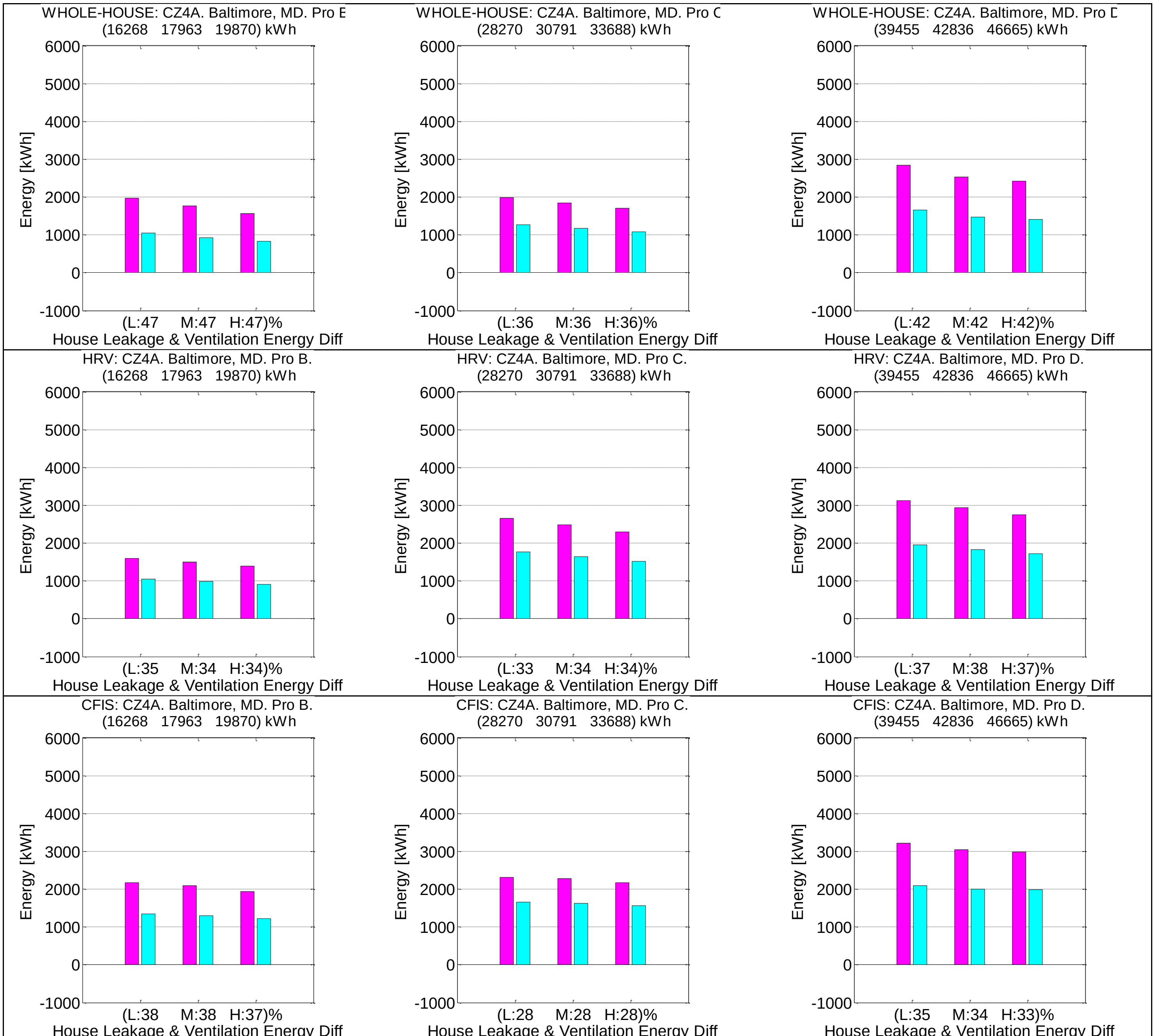


Figure 23: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 3C San Francisco, CA



N/A N/A N/A

Figure 24: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 4A Baltimore, MD

Non-RIVEC RIVEC

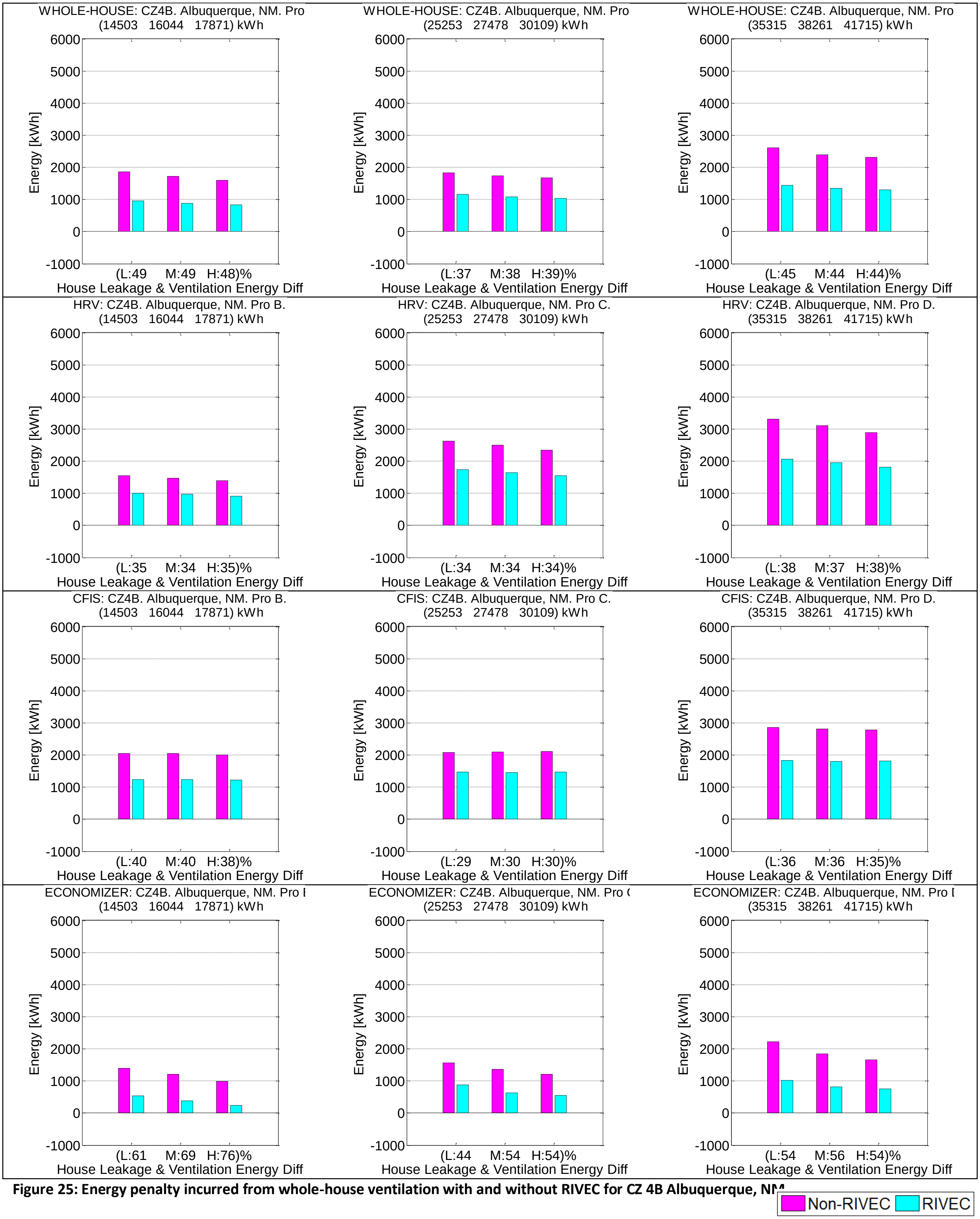


Figure 25: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 4B Albuquerque, NM

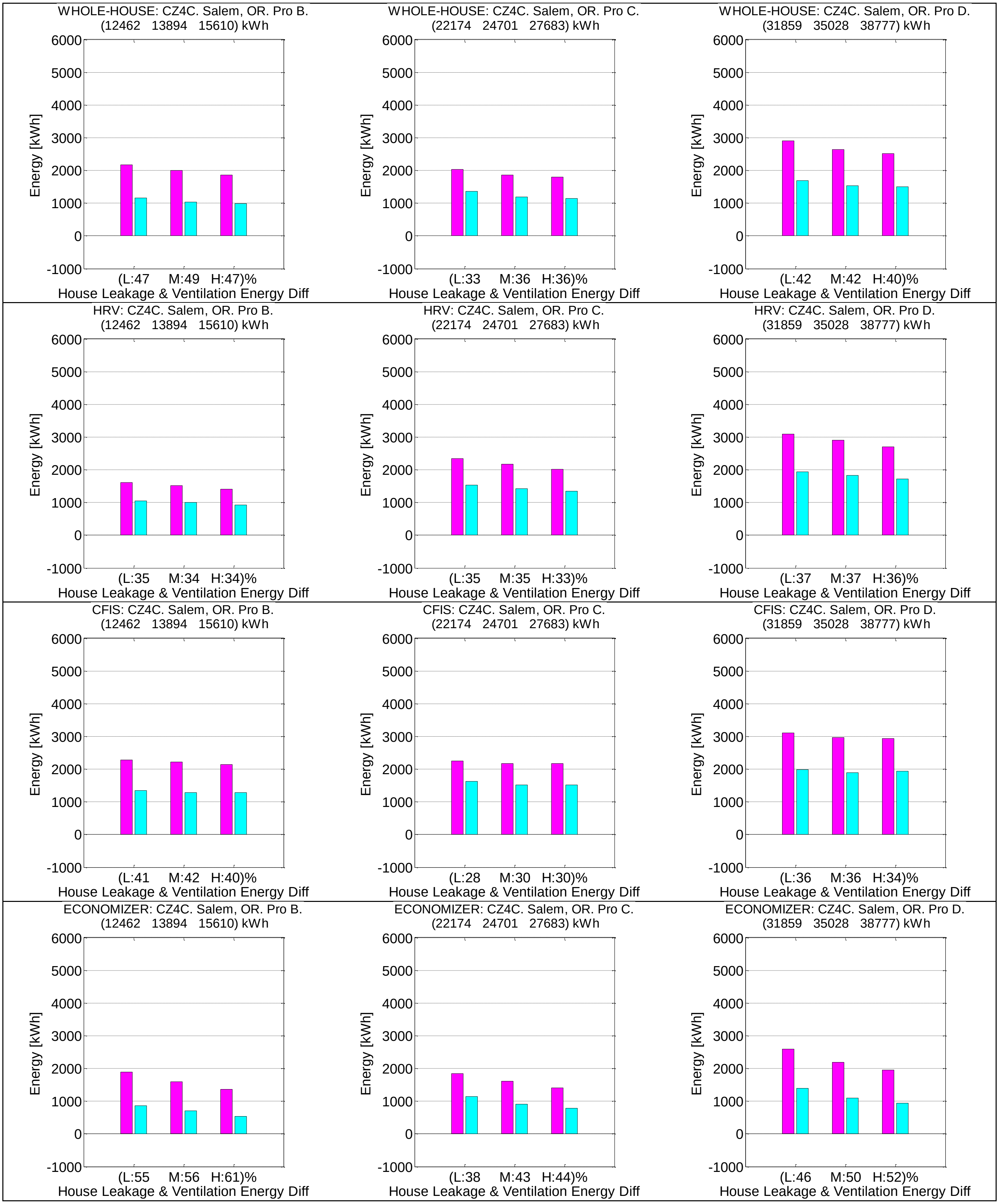
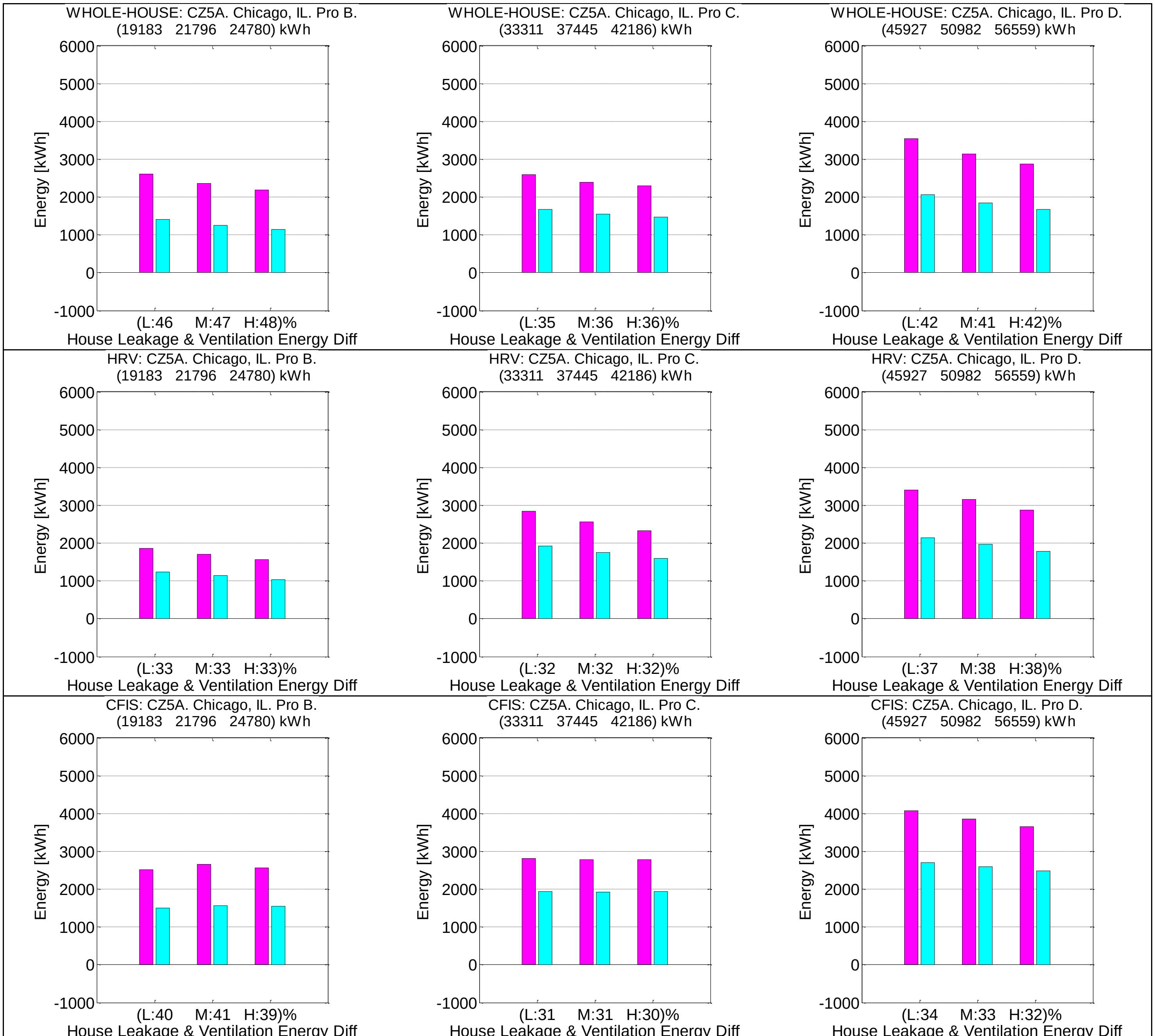


Figure 26: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 4C Salem, OR



N/A N/A N/A

Figure 27: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 5A Chicago, IL

Non-RIVEC RIVEC

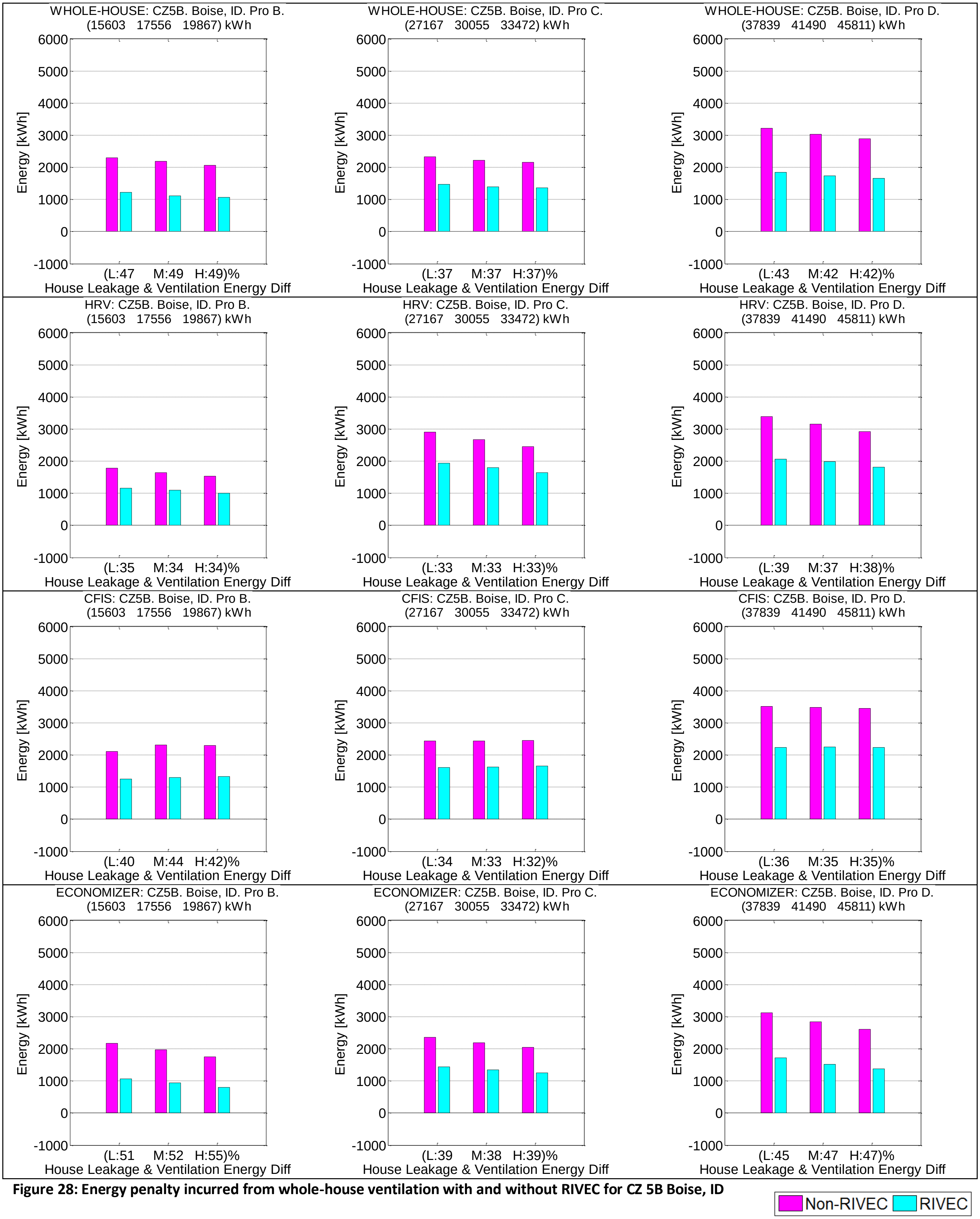
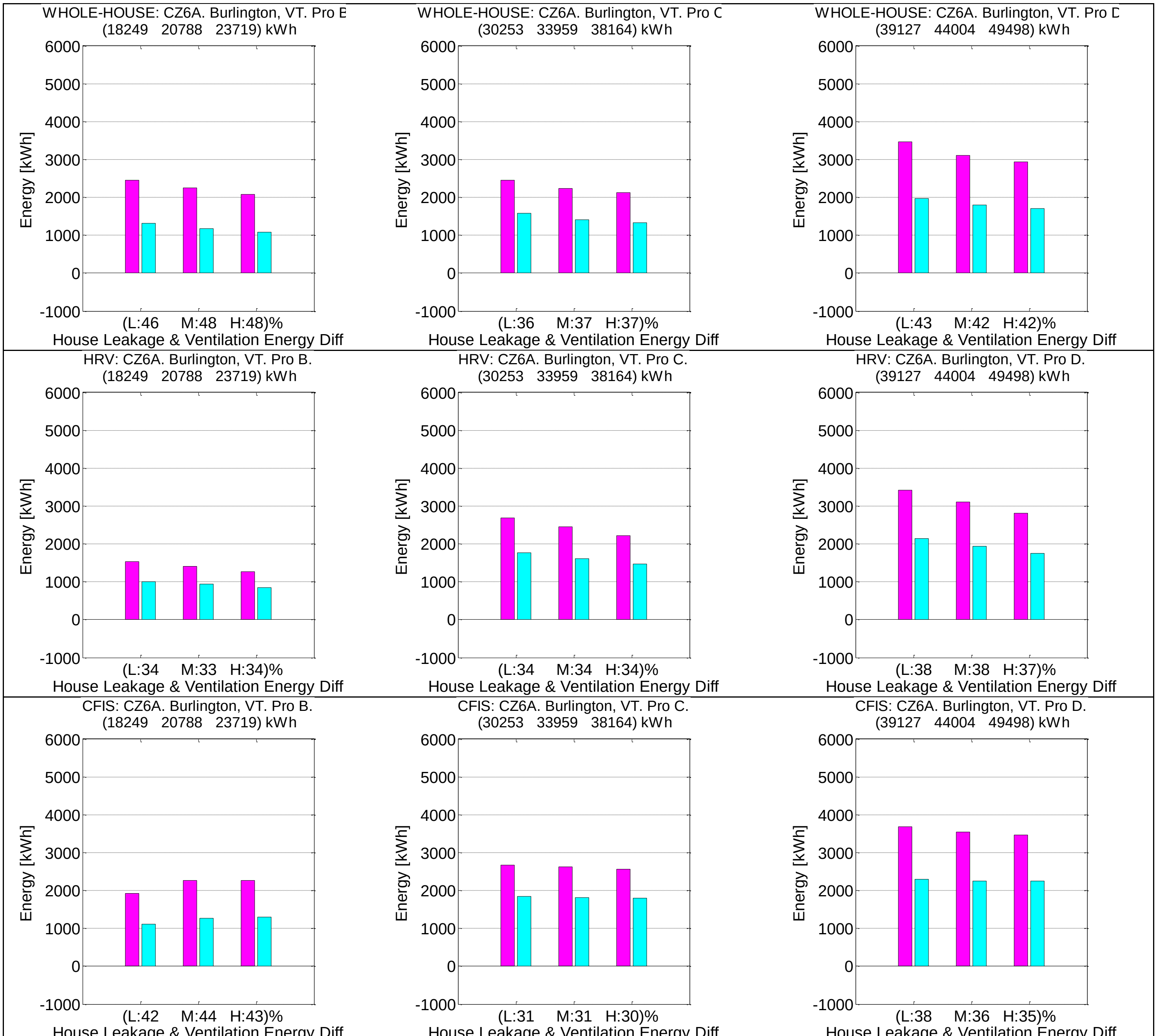


Figure 28: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 5B Boise, ID



N/A

N/A

N/A

Figure 29: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 6A Burlington, VT

Non-RIVEC RIVEC

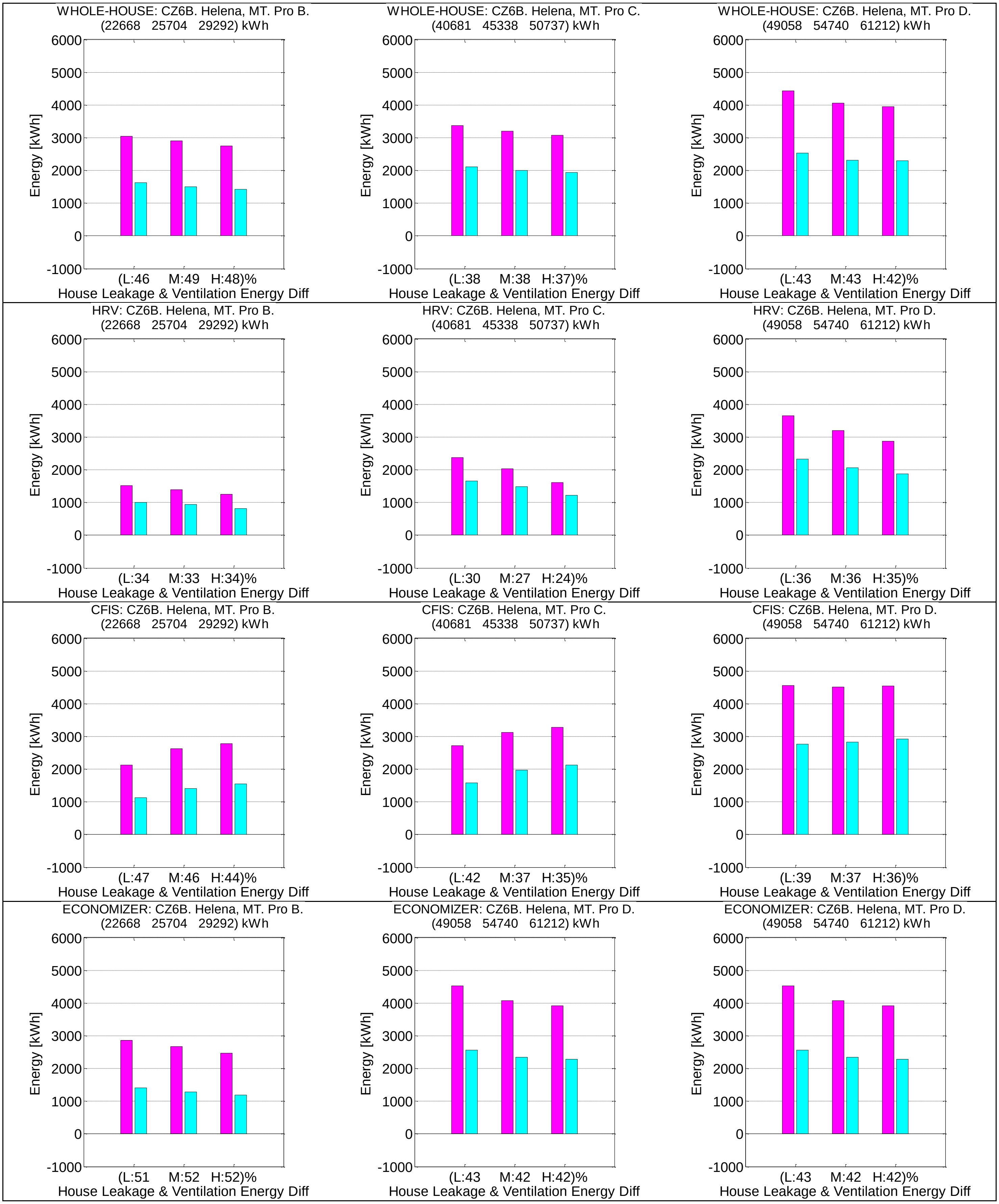


Figure 30: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 6B Helena, MT

Non-RIVEC RIVEC

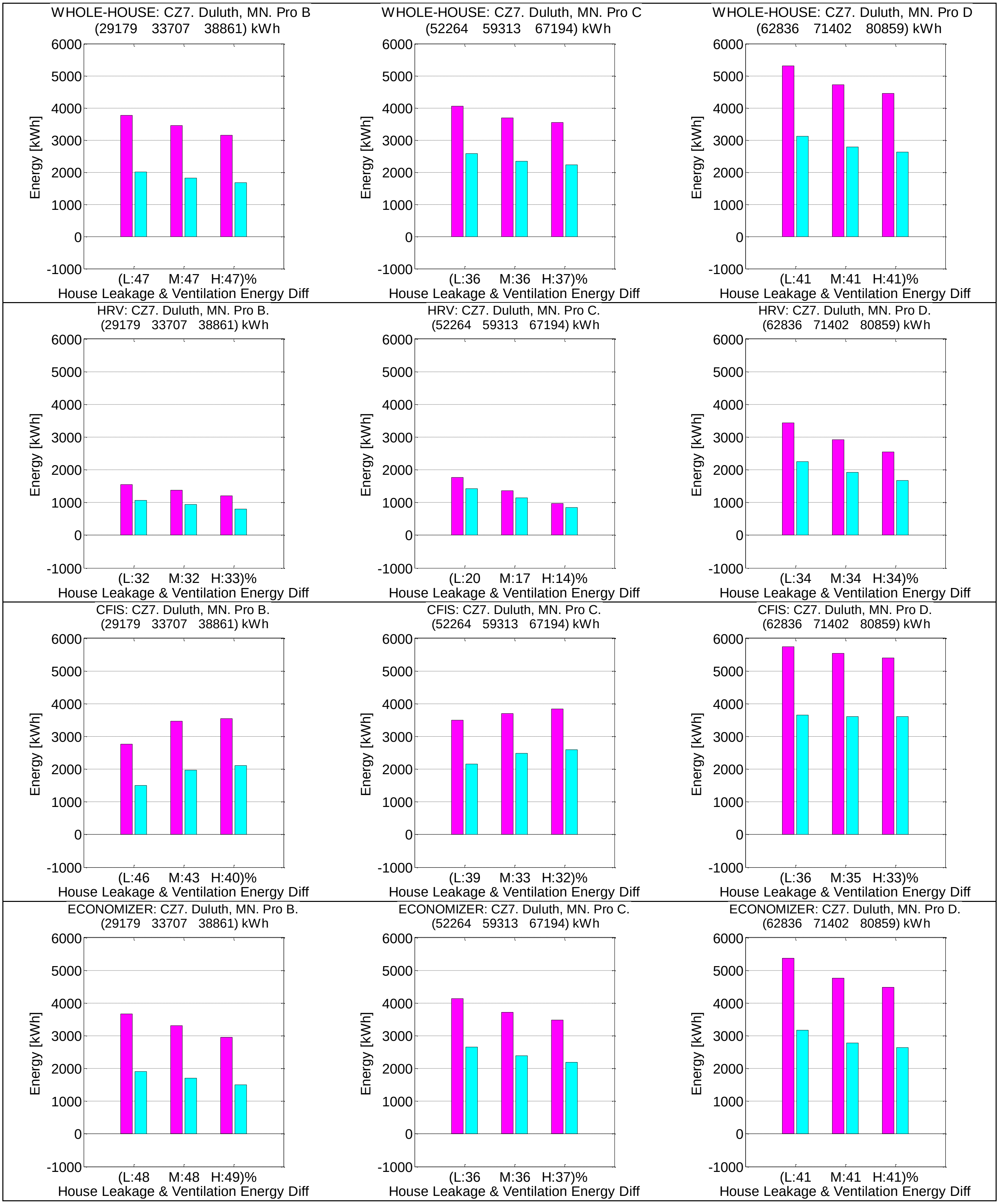


Figure 31: Energy penalty incurred from whole-house ventilation with and without RIVEC for CZ 7 Duluth, MN

Non-RIVEC RIVEC

Appendix B: Critical Peak Load Reduction

Table 17 through Table 20 show the critical peak period power reductions for heating and cooling using RIVEC and the heating/cooling equipment fractional run times.

Table 17: Heating critical peak load reduction [W]

House	Leakage	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Pro B	2.0	930	1621	1309	1169	1231	710	2608	1569	1849	2129	1159	1309	1159
	4.8	770	1179	760	1849	1647	1101	2141	1491	290	2129	1309	1109	760
	8.0	450	1855	460	970	660	1017	1517	2219	1529	970	210	410	160
Pro C	2.0	2310	1460	1135	2709	1378	661	3509	3059	2035	2559	1810	2310	2010
	4.8	2110	1660	536	861	1234	1011	3009	3908	1210	1510	536	1810	1110
	8.0	1011	1610	986	3109	407	11	1960	1860	911	986	1360	1210	1011
Pro D	2.0	4436	2063	3686	3686	514	4886	2712	2562	3761	3761	2312	3312	1413
	4.8	1438	1963	838	2937	1163	2337	5185	2862	2113	2038	1813	414	813
	8.0	14	2262	1588	3836	264	539	2262	3986	1288	14	614	1113	14

Table 18: Furnace fractional run times during critical peak hours

House	Leakage	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Pro B	2.0	71	73	67	64	71	92	67	80	80	63	78	72	84
	4.8	80	82	81	64	65	87	73	81	98	70	90	83	95
	8.0	93	76	95	74	87	88	81	72	87	88	99	97	99
Pro C	2.0	85	68	79	82	87	96	77	76	75	61	81	61	70
	4.8	86	74	86	94	89	93	80	74	87	70	98	71	83
	8.0	93	77	96	79	96	100	87	88	96	80	94	81	93
Pro D	2.0	74	86	84	71	97	78	75	66	83	79	80	72	88
	4.8	92	87	96	77	92	90	75	71	91	91	94	87	97
	8.0	100	85	93	81	98	98	90	80	94	100	98	96	100

Table 19: Cooling critical peak load reduction [W]

House	Leakage	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Pro B	2.0	47	143	24	60	2	34	20	-16	12	-3	40	-17	9
	4.8	43	44	26	56	0	22	35	-2	40	25	33	-7	11
	8.0	37	45	25	25	0	48	-4	28	25	1	30	-4	15
Pro C	2.0	553	111	47	45	-4	28	-1	-9	65	2	34	-21	10
	4.8	49	42	40	36	-1	27	-1	3	13	5	36	-11	13
	8.0	60	60	38	37	1	22	2	7	17	11	32	-3	14
Pro D	2.0	106	718	69	63	1	56	28	-9	22	9	50	187	17
	4.8	71	323	70	59	4	35	28	6	24	8	48	-7	22
	8.0	62	63	60	42	5	27	7	44	162	15	87	0	24

Table 20: Compressor fractional run times during critical peak hours

House	Leakage	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Pro B	2.0	100	97	100	99	75	100	99	100	100	100	100	100	100
	4.8	100	100	100	98	0	100	98	100	99	99	100	100	100
	8.0	100	100	100	100	0	99	100	99	100	100	100	100	100
Pro C	2.0	89	100	100	100	40	100	100	100	98	100	100	100	100
	4.8	100	100	100	100	40	100	100	100	100	100	100	100	100
	8.0	100	100	100	100	40	100	100	100	100	100	100	100	100
Pro D	2.0	100	92	100	100	25	100	99	100	100	100	100	94	100
	4.8	100	97	100	100	25	100	100	100	100	100	100	100	100
	8.0	100	100	100	100	25	100	100	99	96	100	99	100	100

Appendix C: Relative Dose and Exposure

Table 21 through Table 28 show the hourly 'real' occupied relative exposures and doses for all four ventilation strategies, house sizes, envelope leakages and climate zones.

Table 21: Strategy 1b, Whole-House Exhaust. 'Real' Occupied Relative Exposures

House	Leakage	M/M/M	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2 .0 ACH_{50}	Min	0.33	0.34	0.31	0.32	0.33	0.32	0.32	0.32	0.30	0.31	0.31	0.31	0.29
		Max	3.14	3.27	3.16	3.19	3.05	3.28	3.23	3.22	3.25	3.09	3.32	3.20	3.29
		Mean	1.41	1.35	1.35	1.38	1.42	1.35	1.36	1.40	1.31	1.33	1.32	1.30	1.24
	4.8 ACH_{50}	Min	0.30	0.33	0.28	0.31	0.20	0.26	0.30	0.31	0.26	0.27	0.27	0.28	0.25
		Max	2.69	2.84	2.61	2.59	2.42	2.77	2.65	2.76	2.70	2.50	2.87	2.64	2.73
		Mean	1.17	1.14	1.07	1.10	1.09	1.04	1.03	1.05	0.96	0.98	1.00	0.94	0.87
	8.0 ACH_{50}	Min	0.20	0.32	0.21	0.19	0.12	0.18	0.19	0.25	0.16	0.19	0.17	0.19	0.16
		Max	2.30	2.42	2.16	2.12	1.98	2.38	2.23	2.38	2.27	2.02	2.46	2.14	2.29
		Mean	0.96	0.94	0.85	0.88	0.82	0.81	0.79	0.78	0.73	0.73	0.78	0.70	0.64
Prototype C	2 .0 ACH_{50}	Min	0.52	0.53	0.49	0.53	0.55	0.48	0.51	0.52	0.45	0.51	0.50	0.47	0.44
		Max	3.20	3.37	3.23	3.21	3.10	3.33	3.21	3.25	3.35	3.18	3.28	3.20	3.35
		Mean	1.54	1.49	1.47	1.51	1.57	1.47	1.48	1.51	1.39	1.46	1.42	1.41	1.33
	4.8 ACH_{50}	Min	0.37	0.49	0.37	0.37	0.31	0.34	0.30	0.34	0.30	0.33	0.31	0.36	0.27
		Max	2.62	2.82	2.60	2.60	2.32	2.72	2.55	2.55	2.79	2.46	2.65	2.52	2.65
		Mean	1.19	1.21	1.10	1.15	1.12	1.08	1.06	1.05	0.96	1.03	1.01	0.98	0.89
	8.0 ACH_{50}	Min	0.25	0.41	0.24	0.23	0.19	0.23	0.20	0.21	0.19	0.22	0.20	0.25	0.19
		Max	2.14	2.26	2.08	2.07	1.83	2.24	2.05	2.00	2.25	1.91	2.11	1.98	2.08
		Mean	0.93	0.97	0.84	0.87	0.81	0.81	0.78	0.76	0.69	0.75	0.75	0.71	0.64
Prototype D	2 .0 ACH_{50}	Min	0.57	0.64	0.51	0.58	0.60	0.52	0.56	0.58	0.50	0.53	0.47	0.50	0.46
		Max	3.00	2.98	2.95	2.99	2.87	3.09	2.97	3.00	2.93	2.97	3.07	2.97	2.99
		Mean	1.53	1.49	1.47	1.51	1.56	1.48	1.48	1.51	1.40	1.46	1.43	1.42	1.34
	4.8 ACH_{50}	Min	0.38	0.58	0.36	0.35	0.27	0.33	0.34	0.38	0.29	0.33	0.30	0.39	0.28
		Max	2.50	2.51	2.44	2.44	2.23	2.58	2.44	2.43	2.34	2.32	2.55	2.39	2.29
		Mean	1.20	1.22	1.11	1.15	1.11	1.09	1.07	1.05	0.96	1.02	1.02	0.98	0.90
	8.0 ACH_{50}	Min	0.23	0.42	0.23	0.21	0.16	0.21	0.20	0.23	0.19	0.22	0.19	0.25	0.18
		Max	2.04	2.03	2.00	1.92	1.72	2.21	1.96	1.98	1.90	1.84	2.03	1.89	1.74
		Mean	0.94	0.97	0.84	0.88	0.80	0.82	0.78	0.76	0.70	0.74	0.76	0.71	0.64

Table 22: Strategy 1b, Whole-House Exhaust. 'Real' Occupied Relative Doses

House	Leakage	M/M/M	1	2	3	4	5	6	7	8	9	10	11	12	13
Prototype B	2 .0 ACH_{50}	Min	0.92	0.90	0.78	0.99	0.88	0.90	0.92	0.97	0.80	0.91	0.76	0.83	0.75
		Max	1.45	1.48	1.43	1.41	1.44	1.47	1.41	1.41	1.47	1.41	1.43	1.41	1.49
		Mean	1.21	1.15	1.17	1.18	1.21	1.17	1.17	1.19	1.14	1.15	1.15	1.14	1.10
	4.8 ACH_{50}	Min	0.64	0.77	0.50	0.72	0.65	0.58	0.60	0.66	0.51	0.61	0.48	0.52	0.46
		Max	1.29	1.33	1.29	1.26	1.27	1.32	1.22	1.22	1.28	1.18	1.27	1.22	1.26
		Mean	1.06	1.03	1.00	1.01	1.00	0.97	0.96	0.97	0.92	0.93	0.95	0.91	0.86
	8.0 ACH_{50}	Min	0.48	0.64	0.37	0.55	0.46	0.42	0.42	0.49	0.37	0.45	0.35	0.37	0.33
		Max	1.17	1.18	1.15	1.11	1.07	1.16	1.04	1.06	1.11	1.01	1.16	1.05	1.08
		Mean	0.93	0.90	0.86	0.86	0.82	0.82	0.79	0.80	0.76	0.76	0.80	0.74	0.70
Prototype C	2 .0 ACH_{50}	Min	1.02	0.96	0.84	1.06	1.02	0.95	1.02	0.99	0.83	0.96	0.81	0.87	0.77
		Max	1.61	1.68	1.59	1.57	1.60	1.63	1.56	1.61	1.61	1.61	1.58	1.57	1.65
		Mean	1.32	1.27	1.28	1.30	1.33	1.28	1.28	1.30	1.23	1.27	1.25	1.24	1.18
	4.8 ACH_{50}	Min	0.69	0.79	0.54	0.75	0.72	0.61	0.65	0.63	0.53	0.64	0.50	0.54	0.47
		Max	1.39	1.50	1.40	1.38	1.32	1.45	1.32	1.32	1.40	1.28	1.40	1.30	1.35
		Mean	1.10	1.10	1.04	1.06	1.03	1.02	1.00	1.00	0.93	0.98	0.98	0.94	0.89
	8.0 ACH_{50}	Min	0.51	0.64	0.39	0.55	0.53	0.43	0.45	0.43	0.38	0.47	0.35	0.38	0.33
		Max	1.21	1.26	1.19	1.16	1.05	1.28	1.08	1.12	1.16	1.05	1.20	1.08	1.12
		Mean	0.92	0.93	0.86	0.87	0.82	0.83	0.80	0.79	0.74	0.78	0.79	0.75	0.71
Prototype D	2 .0 ACH_{50}	Min	1.03	1.00	0.86	1.09	1.01	0.94	1.01	1.01	0.85	0.98	0.82	0.89	0.79
		Max	1.64	1.69	1.62	1.59	1.62	1.66	1.60	1.65	1.63	1.62	1.58	1.60	1.68
		Mean	1.34	1.30	1.30	1.32	1.35	1.30	1.30	1.32	1.25	1.29	1.27	1.26	1.20
	4.8 ACH_{50}	Min	0.68	0.82	0.53	0.76	0.70	0.61	0.63	0.65	0.54	0.65	0.50	0.54	0.48
		Max	1.41	1.50	1.42	1.39	1.35	1.48	1.34	1.36	1.38	1.28	1.44	1.33	1.33
		Mean	1.12	1.12	1.05	1.07	1.04	1.03	1.01	1.01	0.94	0.98	0.99	0.96	0.90
	8.0 ACH_{50}	Min	0.50	0.65	0.39	0.56	0.51	0.43	0.44	0.45	0.38	0.47	0.35	0.38	0.33
		Max	1.22	1.27	1.23	1.15	1.05	1.26	1.10	1.14	1.13	1.06	1.23	1.10	1.11
		Mean	0.93	0.94	0.86	0.88	0.82	0.84	0.81	0.80	0.75	0.78	0.80	0.76	0.71

Table 23: Strategy 2b, HRV. 'Real' Occupied Relative Exposures

House	Leakage	M/M/M	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2 .0 ACH_{50}	Min	0.31	0.32	0.30	0.31	0.33	0.31	0.31	0.33	0.31	0.31	0.30	0.31	0.30
		Max	3.53	3.63	3.63	3.64	3.53	3.75	3.66	3.76	3.72	3.52	3.79	3.70	3.88
		Mean	1.23	1.14	1.17	1.19	1.26	1.18	1.18	1.21	1.14	1.14	1.17	1.14	1.09
	4.8 ACH_{50}	Min	0.27	0.31	0.25	0.25	0.19	0.24	0.26	0.30	0.20	0.26	0.22	0.24	0.23
		Max	2.91	3.15	2.88	2.84	2.69	3.04	3.00	2.90	2.98	2.77	3.22	2.95	3.06
		Mean	0.98	0.94	0.90	0.93	0.94	0.89	0.88	0.90	0.83	0.83	0.87	0.82	0.77
	8.0 ACH_{50}	Min	0.18	0.28	0.17	0.18	0.12	0.18	0.17	0.21	0.14	0.18	0.16	0.17	0.16
		Max	2.46	2.77	2.37	2.36	2.09	2.53	2.51	2.55	2.46	2.23	2.75	2.36	2.54
		Mean	0.81	0.78	0.72	0.75	0.72	0.70	0.69	0.69	0.64	0.64	0.68	0.62	0.58
Prototype C	2 .0 ACH_{50}	Min	0.48	0.46	0.47	0.42	0.52	0.48	0.47	0.42	0.39	0.50	0.42	0.44	0.41
		Max	3.16	3.19	3.23	3.21	3.22	3.41	3.28	3.37	3.40	3.08	3.33	3.25	3.39
		Mean	1.24	1.15	1.18	1.20	1.33	1.21	1.20	1.25	1.15	1.19	1.19	1.16	1.12
	4.8 ACH_{50}	Min	0.31	0.37	0.29	0.28	0.27	0.30	0.30	0.26	0.23	0.32	0.26	0.32	0.25
		Max	2.56	2.69	2.61	2.56	2.39	2.76	2.57	2.54	2.82	2.39	2.65	2.54	2.70
		Mean	0.95	0.93	0.89	0.92	0.95	0.89	0.88	0.89	0.80	0.85	0.85	0.83	0.77
	8.0 ACH_{50}	Min	0.23	0.30	0.21	0.20	0.17	0.22	0.20	0.18	0.17	0.22	0.18	0.23	0.18
		Max	2.06	2.33	2.10	2.06	1.83	2.25	2.03	2.03	2.33	1.87	2.13	2.03	2.15
		Mean	0.76	0.76	0.69	0.72	0.71	0.69	0.67	0.67	0.60	0.65	0.65	0.62	0.56
Prototype D	2 .0 ACH_{50}	Min	0.49	0.48	0.47	0.48	0.47	0.45	0.51	0.47	0.38	0.52	0.42	0.48	0.42
		Max	3.28	3.21	3.20	3.21	3.21	3.46	3.29	3.33	3.27	3.16	3.33	3.24	3.35
		Mean	1.22	1.16	1.18	1.20	1.30	1.22	1.20	1.23	1.15	1.19	1.19	1.17	1.12
	4.8 ACH_{50}	Min	0.31	0.39	0.31	0.30	0.24	0.28	0.30	0.29	0.23	0.29	0.25	0.30	0.26
		Max	2.67	2.56	2.50	2.54	2.42	2.72	2.56	2.53	2.52	2.39	2.69	2.56	2.54
		Mean	0.95	0.94	0.89	0.92	0.93	0.90	0.88	0.88	0.81	0.86	0.86	0.83	0.77
	8.0 ACH_{50}	Min	0.21	0.30	0.21	0.19	0.15	0.20	0.19	0.21	0.16	0.22	0.17	0.22	0.18
		Max	2.14	2.12	2.01	2.05	1.85	2.17	2.04	2.04	2.04	1.86	2.16	2.02	1.87
		Mean	0.76	0.77	0.69	0.73	0.70	0.69	0.67	0.67	0.61	0.65	0.65	0.62	0.57

Table 24: Strategy 2b, HRV. 'Real' Occupied Relative Doses

House	Leakage	M/M/M	1	2	3	4	5	6	7	8	9	10	11	12	13
Prototype B	2 .0 ACH_{50}	Min	0.76	0.78	0.66	0.79	0.77	0.76	0.78	0.81	0.69	0.76	0.66	0.71	0.66
		Max	1.26	1.18	1.26	1.24	1.24	1.30	1.27	1.29	1.27	1.20	1.32	1.28	1.35
		Mean	1.03	0.96	0.99	0.99	1.04	1.00	1.00	1.01	0.97	0.97	1.01	0.98	0.95
	4.8 ACH_{50}	Min	0.55	0.66	0.45	0.59	0.55	0.52	0.53	0.58	0.46	0.54	0.44	0.47	0.42
		Max	1.10	1.06	1.10	1.09	1.03	1.15	1.09	1.05	1.10	1.02	1.16	1.09	1.08
		Mean	0.89	0.84	0.84	0.84	0.85	0.83	0.82	0.82	0.79	0.79	0.83	0.78	0.75
	8.0 ACH_{50}	Min	0.43	0.55	0.34	0.47	0.41	0.38	0.39	0.45	0.34	0.41	0.33	0.34	0.31
		Max	0.98	0.97	0.99	0.99	0.91	1.04	0.95	0.92	0.98	0.91	1.04	0.95	0.96
		Mean	0.78	0.75	0.73	0.73	0.72	0.71	0.70	0.70	0.67	0.67	0.71	0.66	0.63
Prototype C	2 .0 ACH_{50}	Min	0.84	0.79	0.71	0.84	0.88	0.81	0.85	0.83	0.73	0.81	0.71	0.73	0.68
		Max	1.27	1.19	1.25	1.27	1.29	1.35	1.29	1.32	1.34	1.29	1.34	1.30	1.31
		Mean	1.06	0.98	1.03	1.03	1.11	1.04	1.03	1.07	1.01	1.03	1.04	1.01	0.99
	4.8 ACH_{50}	Min	0.60	0.65	0.48	0.61	0.63	0.54	0.58	0.55	0.49	0.57	0.46	0.49	0.44
		Max	1.09	1.06	1.08	1.12	1.04	1.19	1.07	1.12	1.16	1.06	1.16	1.10	1.10
		Mean	0.88	0.85	0.84	0.85	0.88	0.84	0.83	0.84	0.79	0.82	0.83	0.80	0.77
	8.0 ACH_{50}	Min	0.46	0.54	0.37	0.47	0.47	0.40	0.42	0.40	0.35	0.43	0.33	0.35	0.31
		Max	0.97	0.95	0.95	0.99	0.91	1.06	0.93	0.92	1.02	0.92	1.03	0.95	0.97
		Mean	0.76	0.75	0.72	0.73	0.73	0.71	0.70	0.70	0.66	0.68	0.69	0.67	0.63
Prototype D	2 .0 ACH_{50}	Min	0.84	0.82	0.72	0.85	0.85	0.81	0.83	0.85	0.74	0.84	0.71	0.76	0.69
		Max	1.29	1.23	1.27	1.27	1.29	1.36	1.29	1.35	1.35	1.30	1.37	1.33	1.31
		Mean	1.06	1.01	1.03	1.04	1.11	1.07	1.05	1.07	1.02	1.05	1.06	1.03	1.00
	4.8 ACH_{50}	Min	0.59	0.68	0.48	0.61	0.61	0.54	0.56	0.56	0.49	0.58	0.46	0.49	0.44
		Max	1.11	1.08	1.08	1.12	1.05	1.18	1.08	1.06	1.13	1.08	1.19	1.10	1.12
		Mean	0.89	0.87	0.85	0.86	0.87	0.86	0.84	0.85	0.80	0.83	0.84	0.81	0.77
	8.0 ACH_{50}	Min	0.45	0.56	0.37	0.47	0.45	0.39	0.40	0.41	0.35	0.43	0.33	0.36	0.32
		Max	0.98	0.96	0.95	0.99	0.90	1.04	0.95	0.93	0.97	0.93	1.05	0.95	0.98
		Mean	0.77	0.76	0.73	0.74	0.72	0.72	0.70	0.70	0.66	0.69	0.70	0.67	0.64

Table 25: Strategy 3b, CFIS + Whole-House Exhaust. 'Real' Occupied Relative Exposures

House	Leakage	M/M/M	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2 .0 ACH_{50}	Min	0.33	0.33	0.30	0.32	0.33	0.30	0.32	0.32	0.29	0.31	0.30	0.30	0.28
		Max	3.13	3.26	3.14	3.19	2.89	3.28	3.23	3.22	3.24	3.09	3.30	3.20	3.29
		Mean	1.34	1.26	1.28	1.31	1.33	1.25	1.26	1.31	1.24	1.26	1.24	1.24	1.17
	4.8 ACH_{50}	Min	0.28	0.33	0.28	0.31	0.19	0.24	0.27	0.31	0.23	0.26	0.24	0.27	0.23
		Max	2.65	2.85	2.61	2.59	2.33	2.78	2.61	2.74	2.70	2.50	2.84	2.63	2.73
		Mean	1.12	1.08	1.03	1.06	1.03	0.98	0.97	0.99	0.92	0.94	0.96	0.91	0.84
	8.0 ACH_{50}	Min	0.18	0.32	0.19	0.19	0.12	0.17	0.18	0.23	0.15	0.18	0.16	0.18	0.15
		Max	2.28	2.43	2.16	2.12	1.92	2.38	2.21	2.38	2.27	2.02	2.44	2.15	2.29
		Mean	0.93	0.89	0.83	0.85	0.78	0.77	0.75	0.75	0.70	0.71	0.74	0.68	0.62
Prototype C	2 .0 ACH_{50}	Min	0.50	0.52	0.47	0.51	0.53	0.46	0.49	0.49	0.43	0.50	0.47	0.46	0.42
		Max	3.20	3.36	3.21	3.21	2.96	3.33	3.21	3.18	3.35	3.18	3.27	3.20	3.35
		Mean	1.46	1.41	1.40	1.43	1.44	1.38	1.38	1.42	1.33	1.40	1.35	1.36	1.27
	4.8 ACH_{50}	Min	0.35	0.47	0.34	0.35	0.28	0.32	0.30	0.31	0.27	0.32	0.29	0.35	0.26
		Max	2.60	2.81	2.59	2.60	2.22	2.72	2.54	2.50	2.79	2.46	2.63	2.52	2.65
		Mean	1.15	1.17	1.06	1.10	1.04	1.03	1.02	1.01	0.93	0.99	0.97	0.95	0.86
	8.0 ACH_{50}	Min	0.24	0.39	0.22	0.22	0.18	0.22	0.20	0.20	0.18	0.21	0.19	0.24	0.18
		Max	2.14	2.29	2.08	2.07	1.76	2.24	2.04	2.00	2.24	1.91	2.11	1.98	2.08
		Mean	0.90	0.94	0.81	0.85	0.77	0.78	0.76	0.74	0.67	0.73	0.73	0.70	0.62
Prototype D	2 .0 ACH_{50}	Min	0.54	0.62	0.49	0.56	0.55	0.48	0.53	0.55	0.46	0.51	0.45	0.48	0.44
		Max	2.99	2.98	2.95	2.99	2.69	3.09	2.97	2.99	2.93	2.97	3.06	2.97	2.96
		Mean	1.47	1.41	1.40	1.44	1.44	1.39	1.39	1.43	1.31	1.38	1.36	1.35	1.26
	4.8 ACH_{50}	Min	0.35	0.54	0.32	0.34	0.25	0.30	0.31	0.35	0.27	0.31	0.27	0.36	0.26
		Max	2.50	2.51	2.44	2.44	2.14	2.58	2.44	2.43	2.31	2.32	2.55	2.39	2.28
		Mean	1.16	1.16	1.06	1.11	1.04	1.04	1.02	1.01	0.92	0.98	0.98	0.95	0.86
	8.0 ACH_{50}	Min	0.22	0.38	0.22	0.21	0.16	0.20	0.19	0.21	0.18	0.21	0.18	0.24	0.17
		Max	2.04	2.02	2.00	1.92	1.67	2.21	1.97	1.98	1.85	1.85	2.02	1.89	1.74
		Mean	0.91	0.93	0.82	0.85	0.77	0.79	0.76	0.74	0.67	0.72	0.73	0.69	0.62

Table 26: Strategy 3b, CFIS + Whole-House Exhaust. 'Real' Occupied Relative Doses

House	Leakage	M/M/M	1	2	3	4	5	6	7	8	9	10	11	12	13
Prototype B	2 .0 ACH_{50}	Min	0.83	0.81	0.69	0.91	0.83	0.77	0.79	0.84	0.69	0.82	0.68	0.75	0.67
		Max	1.43	1.48	1.43	1.39	1.43	1.47	1.40	1.41	1.45	1.41	1.43	1.40	1.49
		Mean	1.16	1.10	1.13	1.13	1.16	1.11	1.11	1.14	1.10	1.11	1.10	1.10	1.06
	4.8 ACH_{50}	Min	0.59	0.70	0.46	0.67	0.60	0.51	0.52	0.59	0.46	0.56	0.45	0.48	0.42
		Max	1.27	1.33	1.29	1.23	1.25	1.32	1.21	1.22	1.27	1.18	1.24	1.21	1.26
		Mean	1.03	0.99	0.97	0.98	0.97	0.93	0.92	0.94	0.89	0.90	0.92	0.88	0.84
	8.0 ACH_{50}	Min	0.45	0.59	0.35	0.52	0.44	0.38	0.38	0.45	0.34	0.42	0.33	0.34	0.30
		Max	1.15	1.18	1.14	1.09	1.06	1.16	1.03	1.06	1.09	1.01	1.11	1.02	1.07
		Mean	0.91	0.87	0.84	0.83	0.80	0.79	0.77	0.77	0.74	0.74	0.78	0.72	0.69
Prototype C	2 .0 ACH_{50}	Min	0.89	0.90	0.74	1.00	0.95	0.84	0.89	0.88	0.75	0.88	0.73	0.80	0.71
		Max	1.60	1.68	1.58	1.56	1.57	1.63	1.55	1.61	1.61	1.61	1.57	1.57	1.65
		Mean	1.27	1.23	1.23	1.24	1.26	1.22	1.21	1.25	1.18	1.23	1.20	1.20	1.14
	4.8 ACH_{50}	Min	0.63	0.73	0.50	0.72	0.68	0.55	0.58	0.57	0.49	0.60	0.47	0.50	0.44
		Max	1.38	1.50	1.38	1.36	1.29	1.45	1.28	1.32	1.40	1.28	1.37	1.27	1.35
		Mean	1.07	1.07	1.01	1.02	0.99	0.98	0.96	0.97	0.91	0.95	0.95	0.92	0.87
	8.0 ACH_{50}	Min	0.47	0.60	0.37	0.53	0.49	0.40	0.42	0.41	0.36	0.44	0.33	0.36	0.31
		Max	1.18	1.26	1.18	1.14	1.03	1.28	1.06	1.12	1.16	1.04	1.18	1.05	1.11
		Mean	0.90	0.91	0.84	0.85	0.79	0.81	0.78	0.78	0.73	0.77	0.77	0.74	0.69
Prototype D	2 .0 ACH_{50}	Min	0.91	0.93	0.73	1.03	0.94	0.84	0.89	0.91	0.73	0.86	0.73	0.80	0.70
		Max	1.63	1.69	1.60	1.57	1.61	1.66	1.59	1.65	1.63	1.62	1.57	1.60	1.68
		Mean	1.29	1.24	1.25	1.27	1.29	1.24	1.24	1.27	1.19	1.23	1.22	1.22	1.16
	4.8 ACH_{50}	Min	0.63	0.75	0.48	0.73	0.67	0.55	0.57	0.59	0.49	0.59	0.47	0.50	0.44
		Max	1.41	1.50	1.41	1.37	1.32	1.46	1.32	1.36	1.37	1.28	1.40	1.30	1.33
		Mean	1.09	1.08	1.02	1.04	1.00	1.00	0.98	0.98	0.91	0.95	0.96	0.93	0.87
	8.0 ACH_{50}	Min	0.47	0.61	0.37	0.54	0.48	0.40	0.41	0.43	0.35	0.44	0.33	0.36	0.31
		Max	1.19	1.26	1.22	1.15	1.03	1.26	1.08	1.14	1.13	1.06	1.19	1.07	1.11
		Mean	0.91	0.92	0.84	0.86	0.80	0.82	0.79	0.78	0.73	0.77	0.78	0.75	0.70

Table 27: Strategy 4b, Economizer + Whole-House Exhaust. 'Real' Occupied Relative Exposures

House	Leakage	M/M/M	2A	2B	3A	3B	3C	4A	4B	4C	5A	5B	6A	6B	7
Prototype B	2 .0 ACH_{50}	Min	-	0.06	-	0.05	0.08	-	0.08	0.10	-	0.06	-	0.05	0.07
		Max	-	2.48	-	2.39	2.31	-	2.39	2.47	-	2.32	-	2.42	2.50
		Mean	-	1.19	-	1.18	1.30	-	1.14	1.25	-	1.18	-	1.18	1.13
	4.8 ACH_{50}	Min	-	0.06	-	0.05	0.08	-	0.08	0.10	-	0.06	-	0.05	0.07
		Max	-	2.21	-	2.09	2.01	-	2.08	2.24	-	1.99	-	2.14	2.24
		Mean	-	1.02	-	0.96	1.02	-	0.87	0.95	-	0.87	-	0.86	0.80
	8.0 ACH_{50}	Min	-	0.06	-	0.05	0.08	-	0.08	0.10	-	0.06	-	0.05	0.07
		Max	-	1.96	-	1.82	1.74	-	1.86	2.00	-	1.69	-	1.85	2.00
		Mean	-	0.86	-	0.78	0.78	-	0.68	0.73	-	0.66	-	0.65	0.60
Prototype C	2 .0 ACH_{50}	Min	-	0.04	-	0.05	0.12	-	0.06	0.10	-	0.06	-	0.05	0.05
		Max	-	3.15	-	3.10	2.97	-	3.09	3.14	-	2.96	-	3.12	3.23
		Mean	-	1.31	-	1.30	1.45	-	1.24	1.35	-	1.28	-	1.29	1.24
	4.8 ACH_{50}	Min	-	0.04	-	0.05	0.11	-	0.06	0.10	-	0.06	-	0.05	0.05
		Max	-	2.67	-	2.53	2.34	-	2.53	2.60	-	2.34	-	2.55	2.67
		Mean	-	1.08	-	0.99	1.06	-	0.90	0.95	-	0.91	-	0.90	0.84
	8.0 ACH_{50}	Min	-	0.04	-	0.05	0.11	-	0.06	0.10	-	0.06	-	0.05	0.05
		Max	-	2.20	-	1.99	1.87	-	2.07	2.10	-	1.86	-	2.11	2.10
		Mean	-	0.88	-	0.77	0.78	-	0.68	0.70	-	0.67	-	0.66	0.60
Prototype D	2 .0 ACH_{50}	Min	-	0.04	-	0.05	0.09	-	0.07	0.09	-	0.07	-	0.06	0.07
		Max	-	2.92	-	2.91	2.76	-	2.87	3.00	-	2.74	-	2.88	2.87
		Mean	-	1.30	-	1.28	1.45	-	1.23	1.35	-	1.27	-	1.29	1.24
	4.8 ACH_{50}	Min	-	0.04	-	0.05	0.09	-	0.07	0.09	-	0.06	-	0.06	0.06
		Max	-	2.51	-	2.39	2.25	-	2.40	2.49	-	2.18	-	2.37	2.29
		Mean	-	1.08	-	0.98	1.06	-	0.89	0.96	-	0.90	-	0.89	0.83
	8.0 ACH_{50}	Min	-	0.04	-	0.05	0.08	-	0.07	0.09	-	0.06	-	0.06	0.06
		Max	-	2.10	-	1.90	1.81	-	1.98	2.03	-	1.75	-	1.95	1.81
		Mean	-	0.88	-	0.77	0.78	-	0.67	0.71	-	0.66	-	0.66	0.60

Table 28: Strategy 4b, Economizer + Whole-House Exhaust. 'Real' Occupied Relative Doses

House	Leakage	M/M/M	1	2	3	4	5	6	7	8	9	10	11	12	13
Prototype B	2 .0 ACH_{50}	Min	-	0.73	-	0.68	0.80	-	0.63	0.74	-	0.66	-	0.67	0.70
		Max	-	1.37	-	1.38	1.41	-	1.29	1.42	-	1.42	-	1.37	1.41
		Mean	-	1.05	-	1.05	1.14	-	1.02	1.10	-	1.05	-	1.06	1.04
	4.8 ACH_{50}	Min	-	0.65	-	0.62	0.65	-	0.58	0.65	-	0.56	-	0.52	0.46
		Max	-	1.20	-	1.20	1.22	-	1.13	1.17	-	1.19	-	1.16	1.19
		Mean	-	0.95	-	0.90	0.96	-	0.83	0.90	-	0.84	-	0.84	0.81
	8.0 ACH_{50}	Min	-	0.59	-	0.51	0.46	-	0.42	0.49	-	0.42	-	0.37	0.33
		Max	-	1.07	-	1.06	1.03	-	0.96	1.00	-	0.95	-	0.97	0.98
		Mean	-	0.84	-	0.78	0.80	-	0.71	0.75	-	0.70	-	0.70	0.67
Prototype C	2 .0 ACH_{50}	Min	-	0.74	-	0.70	0.81	-	0.66	0.75	-	0.70	-	0.73	0.74
		Max	-	1.47	-	1.54	1.52	-	1.46	1.51	-	1.55	-	1.47	1.52
		Mean	-	1.13	-	1.12	1.23	-	1.08	1.16	-	1.12	-	1.13	1.10
	4.8 ACH_{50}	Min	-	0.64	-	0.58	0.66	-	0.52	0.63	-	0.58	-	0.54	0.47
		Max	-	1.31	-	1.29	1.27	-	1.17	1.19	-	1.25	-	1.21	1.26
		Mean	-	0.99	-	0.93	0.98	-	0.85	0.90	-	0.87	-	0.87	0.84
	8.0 ACH_{50}	Min	-	0.56	-	0.48	0.53	-	0.42	0.43	-	0.45	-	0.38	0.33
		Max	-	1.18	-	1.06	1.03	-	0.97	1.03	-	0.97	-	1.00	1.06
		Mean	-	0.85	-	0.78	0.79	-	0.70	0.73	-	0.71	-	0.70	0.67
Prototype D	2 .0 ACH_{50}	Min	-	0.75	-	0.70	0.81	-	0.68	0.78	-	0.72	-	0.69	0.70
		Max	-	1.51	-	1.55	1.54	-	1.47	1.55	-	1.57	-	1.48	1.56
		Mean	-	1.14	-	1.13	1.25	-	1.09	1.18	-	1.13	-	1.14	1.12
	4.8 ACH_{50}	Min	-	0.64	-	0.59	0.70	-	0.53	0.65	-	0.58	-	0.54	0.48
		Max	-	1.28	-	1.30	1.29	-	1.19	1.21	-	1.26	-	1.21	1.28
		Mean	-	1.00	-	0.93	0.99	-	0.86	0.92	-	0.87	-	0.87	0.84
	8.0 ACH_{50}	Min	-	0.57	-	0.48	0.51	-	0.42	0.45	-	0.43	-	0.38	0.33
		Max	-	1.15	-	1.08	1.04	-	0.97	1.04	-	0.97	-	1.00	1.04
		Mean	-	0.86	-	0.78	0.79	-	0.71	0.74	-	0.71	-	0.71	0.68